METHOD FOR FORMING GATE STRUCTURES

Field

The present disclosure relates to processes for forming a plurality of gate structures, and for forming a plurality of electronic devices.

Background

Conductive materials can be used as gate electrodes in electronic devices as well as in other applications. For example, these materials may be deposited and optionally patterned on a substrate prior to coating or deposition of a dielectric material to form an electronic device.

Many electronic devices include a conductive gate electrode adjacent to a gate dielectric. Gate dielectrics act as insulators in electronic devices. Conductive materials can be coated with a dielectric or anodized for forming a gate dielectric adjacent to a gate electrode. Anodizable metals may be oxidized by traditional routes to develop porous or nonporous dielectric layers.

Nonporous or barrier dielectric layers are generally produced anodically in electrolyte solutions, which are relatively noncorrosive toward the conductive metal upon which the dielectric layer is grown. High quality dielectric layers generally are free of pin-holes, and have low leakage current, high breakdown field, and resistance to charge trapping. Barrier dielectric films generally are uniform in thickness.

Anodization of conductive materials, for example as metals, to form dielectric layers can be accomplished in a batch process. The conductive material may be immersed in an electrolyte solution at a certain temperature. An applied voltage can be applied to the electrolyte solution for a period of time to form a dielectric layer on the conductive material as described, for example, in U.S. Patent No. 6,267,861 (Kinard et al.).

The formation of dielectric layers on anodizable materials may be used for numerous applications in electronic devices including electrolytic capacitors, rectifiers, transistors, diodes, light emitting devices, resistors, and combinations thereof.

Summary

The present disclosure describes processes for forming a plurality of gate structures by anodizing a plurality of conductive elements on a substrate of a moving web. Anodization of a portion of the surface of the plurality of conductive elements results in a plurality of gate structures that contain a plurality of gate dielectrics adjacent to a plurality of gate electrodes. A process for forming electronic devices is disclosed that further comprises providing a semiconductor adjacent to the plurality of gate dielectrics, and providing both a source electrode and a drain electrode adjacent to a surface of the semiconductor opposite the plurality of gate structures. Another process for forming electronic devices comprises providing both a source electrode and a drain electrode adjacent to the plurality of gate dielectrics, and further providing a semiconductor adjacent to a surface of both the source electrode and the drain electrode opposite the plurality of gate structures.

In a first aspect, a process is provided for forming a plurality of gate structures. A web is provided that comprises a substrate, a plurality of conductive elements disposed on the substrate, and a conductive anodization bus. The conductive anodization bus is adjacent to a first edge of the substrate. A first conductive element and at least one second conductive element are electrically connected to the conductive anodization bus. The web is moving, such that the web is delivered with a web delivery roll and received with a web receiving roll. The web extends from the web delivery roll to the web receiving roll, and the web passes from the web delivery roll to the web receiving roll. The web passes through an anodization station. The anodization station comprises a anodization bath having an entry location and an exit location for the web; an electrochemical solution retained within the anodization bath, wherein the electrochemical solution has a surface; a cathode located within the electrochemical solution where the plurality of conductive elements is positioned between the substrate and the cathode; an anode; and a power supply attached to the anode and the cathode. The anode comprises the conductive anodization bus where at least a portion of the conductive anodization bus is positioned above the surface of the electrochemical solution; a plurality of conductive elements where at least a portion of the plurality of the conductive elements are positioned below the surface of the electrochemical solution; and a plurality of clamps, where at least one clamp is in electrical contact with the conductive anodization bus. At least a portion of the

surface of the plurality of conductive elements exposed to the electrochemical solution is anodized to form a plurality of gate structures. The plurality of gate structures comprises a plurality of gate dielectrics adjacent to a plurality of gate electrodes. The plurality of gate electrodes is positioned between the plurality of gate dielectrics and the substrate.

In a second aspect, a process is provided for forming a plurality of electronic devices. A web is provided that comprises a substrate, a plurality of conductive elements disposed on the substrate, and a conductive anodization bus. The conductive anodization bus is adjacent to a first edge of the substrate. A first conductive element and at least one second conductive element are electrically connected to the conductive anodization bus. The web is moving, such that the web is delivered with a web delivery roll and received with a web receiving roll. The web extends from the web delivery roll to the web receiving roll, and the web passes from the web delivery roll to the web receiving roll. The web passes through an anodization station. The anodization station comprises an anodization bath having an entry location and an exit location for the web; an electrochemical solution retained within the anodization bath, wherein the electrochemical solution has a surface; a cathode located within the electrochemical solution where the plurality of conductive elements is positioned between the substrate and the cathode; an anode; and a power supply attached to the anode and the cathode. The anode comprises the conductive anodization bus where at least a portion of the conductive anodization bus is positioned above the surface of the electrochemical solution; a plurality of conductive elements where at least a portion of the plurality of the conductive elements are positioned below the surface of the electrochemical solution; and a plurality of clamps, where at least one clamp is in electrical contact with the conductive anodization bus. At least a portion of the surface of the plurality of conductive elements exposed to the electrochemical solution is anodized to form a plurality of gate structures. The plurality of gate structures comprises a plurality of gate dielectrics adjacent to a plurality of gate electrodes. The plurality of gate electrodes is positioned between the plurality of gate dielectrics and the substrate. The process further comprises providing a semiconductor adjacent to the plurality of gate dielectrics. A source electrode and a drain electrode are both provided adjacent to the surface of the semiconductor opposite the plurality of gate structures, such that the source electrode is not in contact with the drain electrode.

In a third aspect, a process is provided for forming a plurality of electronic devices. A web is provided that comprises a substrate, a plurality of conductive elements disposed on the substrate, and a conductive anodization bus. The conductive anodization bus is adjacent to a first edge of the substrate. A first conductive element and at least one second conductive element are electrically connected to the conductive anodization bus. The web is moving, such that the web is delivered with a web delivery roll and received with a web receiving roll. The web extends from the web delivery roll to the web receiving roll, and the web passes from the web delivery roll to the web receiving roll. The web passes through an anodization station. The anodization station comprises a anodization bath having an entry location and an exit location for the web; an electrochemical solution retained within the anodization bath, wherein the electrochemical solution has a surface; a cathode located within the electrochemical solution where the plurality of conductive elements is positioned between the substrate and the cathode; an anode; and a power supply attached to the anode and the cathode. The anode comprises the conductive anodization bus where at least a portion of the conductive anodization bus is positioned above the surface of the electrochemical solution; a plurality of conductive elements where at least a portion of the plurality of the conductive elements are positioned below the surface of the electrochemical solution; and a plurality of clamps, where at least one clamp is in electrical contact with the conductive anodization bus. At least a portion of the surface of the plurality of conductive elements exposed to the electrochemical solution is anodized to form a plurality of gate structures. The plurality of gate structures comprises a plurality of gate dielectrics adjacent to a plurality of gate electrodes. The plurality of gate electrodes is positioned between the plurality of gate dielectrics and the substrate. The process further comprises providing both a source electrode and a drain electrode adjacent to the plurality of gate dielectrics, such that the source electrode is not in contact with the drain electrode. A semiconductor is provided adjacent to the surface of both the source electrode and the drain electrode opposite the plurality of gate structures.

Brief Description of the Drawings

FIG. 1 is a schematic representation of an exemplary web comprising a substrate, a plurality of conductive elements disposed on the substrate, and an anodization bus disposed on the substrate.

FIG. 2 is a schematic representation of a top view of an exemplary anodization station.

FIG. 2A is a schematic representation of an exemplary anode.

FIG. 3 is a schematic representation of a side view of an exemplary anodization station and an exemplary horizontal conveyor for moving a web.

FIG. 4 is a schematic representation of an end view of an exemplary horizontal conveyor for moving a web through an anodization station.

FIG. 5 is a schematic cross-sectional representation of an exemplary web comprising a substrate with a conductive element.

FIG. 6 is a schematic cross-sectional representation of an exemplary gate structure on a web with the gate structure comprising a gate dielectric adjacent to a gate electrode.

FIG. 7 is a schematic cross-sectional representation of **FIG. 6** further comprising a source electrode and a drain electrode adjacent to a gate dielectric, and a semiconductor adjacent to the surface of both the source electrode and the drain electrode of an electronic device.

FIG. 8 is a schematic cross-sectional representation of **FIG. 6** further comprising a semiconductor adjacent to a gate dielectric, and a source electrode and a drain electrode adjacent to the surface of the semiconductor of an electronic device.

Detailed Description

For the following defined terms, these definitions shall be applied, unless a different definition is given in the claims or elsewhere in the specification.

The term "a plurality of" refers to at least two or more of an object, device, or compound. For example, a plurality of conductive elements refers to at least two or more conductive elements.

The term "conductive element" refers to a structure that is capable of transmitting or conducting electrical current. For example, the conductive element may be a metal disposed on a substrate prior to anodization.

The term "gate structure" refers to a gate dielectric adjacent to a gate electrode. The gate dielectric may be formed by anodizing the surface of a conductive element.

The term "gate electrode" refers to a conductive portion of a gate structure, and corresponds to the portion of the conductive element that is not oxidized during the anodization process.

The term "gate dielectric" refers to the nonconductive portion of a gate structure, and corresponds to the portion of the conductive element that is oxidized (for example, anodized) during the anodization process.

The term "web" refers to an article that includes a substrate, a plurality of conductive elements disposed on the substrate, and a conductive anodization bus disposed on the substrate. The web may be flexible, and may be moved from a web delivery roll to a web receiving roll.

The term "anodization station" refers to an anodization bath, an electrochemical solution within the anodization bath, a cathode, an anode, and a power supply. Some exemplary anodization baths comprise a first collection tank, a central tub, and a second collection tank. The anode comprises a conductive anodization bus, a plurality of conductive elements. The anodization station provides for a portion of the surface of the plurality of conductive elements to be anodized, and a plurality of clamps. The anodized conductive elements form a gate structure comprising a gate dielectric adjacent to a gate electrode.

The term "anodization current density" refers to the current per unit area flowing through the surface of an electrode during anodization in units of amperes/square centimeter (A/cm^2).

The term "electrochemical solution" refers to an aqueous solution comprising electrolytes or ionic compounds useful for inducing a chemical change of a material accompanying the passage of an electrical current in the presence of two electrodes. For example, the surface of a metal immersed in an electrochemical solution having an electrical current passing through it may be anodized or oxidized.

The term "conductive anodization bus" refers to a conductive material disposed on a substrate that may be positioned parallel to a first edge of a substrate. For example, the conductive anodization bus may be a narrow band or strip of conductive material for providing an electrical connection between the individual conductive elements of a plurality of conductive elements. The conductive anodization bus remains conductive during the anodization process, and at least a portion of the conductive anodization bus

may be kept out of the electrochemical solution. The conductive anodization bus often provides a location for at least one clamp.

The recitation of numerical ranges by endpoints includes all numbers subsumed within that range (for example, 1 to 5 includes 1, 1.5, 2, 2.75, 3, 3.8, 4, and 5).

As included in this specification and the appended claims, the singular forms "a", "an", and "the" include plural referents unless the content clearly dictates otherwise. Thus, for example, reference to a composition containing "a compound" includes a mixture of two or more compounds. As used in this specification and appended claims, the term "or" is generally employed in its sense including "and/or" unless the content clearly dictates otherwise.

Unless otherwise indicated, all numbers expressing quantities or ingredients, measurement of properties and so forth used in the specification and claims are to be understood as being modified in all instances by the term "about." Accordingly, unless indicated to the contrary, the numerical parameters set forth in the foregoing specification and attached claims are approximations that can vary depending upon the desired properties sought to be obtained by those skilled in the art utilizing the teachings of the present disclosure. Notwithstanding that the numerical ranges and parameters setting forth the broad scope of the disclosure are approximations, the numerical values set forth in the specific examples are reported as precisely as possible. Any numerical value, however, inherently contains errors necessarily resulting from the standard deviations found in their respective testing measurements.

The present disclosure describes a process for forming a plurality of gate structures. A web is provided that has a substrate, a plurality of conductive elements disposed on the substrate, and a conductive anodization bus that is disposed on the substrate. The conductive anodization bus is adjacent to a first edge of the substrate. A first conductive element and at least one second conductive element are electrically connected to the conductive anodization bus. The web passes from a web delivery roll to a web receiving roll, and moves through an anodization station to anodize at least a portion of the surface of the plurality of conductive elements. The anodization station includes an anodization bath, an electrochemical solution within the anodization bath, a cathode, an anode, and a power supply. The anodization bath has an entry location and an exit location for the web. The cathode is located below a surface of the electrochemical

solution. The anode comprises the conductive anodization bus, the plurality of conductive elements, and a plurality of clamps. The power supply is connected to the anode and the cathode. At least a portion of the surface of the plurality of conductive elements are exposed to the electrochemical solution and anodized as the web passes through the anodization station to form a plurality of gate structures. The plurality of gate structures comprises a plurality of gate dielectrics adjacent to a plurality of gate electrodes.

An exemplary web **50** as illustrated in **FIG. 1** comprises a substrate **40**, a plurality of conductive elements **10** disposed on the substrate **40**, and a conductive anodization bus **30** disposed on the substrate **40**. The substrate **40** may provide support for the plurality of conductive elements **10** and for the anodization bus **30**. The conductive elements **10** may be arranged in rows on the substrate **40**. Although the conductive elements **10** in **FIG. 1** are shown as a series of parallel lines, the conductive elements can be patterned in any suitable manner. Further, the substrate **40** can be electrically insulating to prevent shorting during anodization of the plurality of conductive elements **10**. The conductive anodization bus **30** can be parallel to a first edge **5** of the substrate **40**. The plurality of conductive elements **10** are electrically connected to the conductive anodization bus **30**. For example, a first conductive element **15**, and at least a second conductive element **20** are electrically connected to the conductive anodization bus **30**.

A substrate **40** of web **50** may be used to support a deposited or attached material during manufacturing, testing, storage, use, or any combination thereof. The substrate **40** may be permanent, semi-permanent, or removable from the elements or structures that it supports. The substrate **40** may be flexible. For example, the substrate **40** may comprise polymeric materials, filled polymeric materials, acrylics, epoxies, polyamides, polycarbonates, polyimides, polyetherimides, polyketones, liquid crystal polymers, poly(oxy-1,4-phenyleneoxy-1,4-phenylenecarbonyl-1,4-phenylene) (PEEK), polynorbornenes, polyphenyleneoxides, poly(ethylene naphthalenedicarboxylate) (PEN), poly(ethylene terephthalate) (PET), poly(phenylene sulfide) (PPS), and fiber-reinforced plastics (FRP). In some embodiments, a substrate **40**, which is flexible, may comprise poly(ethylene terephthalate) (PET), poly(ethylene naphthalenedicarboxylate) (PEN), poly(ether ether ketone), or combinations thereof.

Generally, a plurality of conductive elements **10** and a conductive anodization bus **30** may be components of a web **50** formed by depositing and patterning an electrically

conductive layer, such as a metal layer, on a substrate **40** or substrate material. An adhesion layer may be applied to the substrate **40** prior to the deposition of the conductive layer. The adhesion layer may comprise an inorganic oxide, for example, SiO_x. The conductive layer may be deposited using any suitable known method such as thermal evaporation, e-beam evaporation, sputtering, flame hydrolysis, casting, plasma deposition or any other deposition method that may be desirable in an application. The conductive layer on the substrate **40** may be patterned by a series of steps.

A plurality of conductive elements **10** and a conductive anodization bus **30** can be formed from a patterned conductive layer. Some of the processing steps used to form the patterned conductive layer may include laminating or coating a photoresist layer (not shown) onto an electrically conductive layer of **FIG. 1**. After application of the photoresist layer, the conductive layer may be masked with an aperture mask, and subsequently exposed to a radiation source. For example, the material exposed to radiation is typically cured while the masked material is not typically cured. The uncured material can be removed. The photoresist layer may be developed (for example, selectively removed), followed by etching of the conductive layer with a caustic or acidic solution. The photoresist layer may be stripped from the conductive layer and the substrate **40**. The web **50** may be rinsed and cleaned in a series of steps to provide the patterned conductive elements (for example, plurality of conductive elements **10**) and the conductive anodization bus **30** disposed on the substrate **40**.

A plurality of conductive elements **10** may be any material that is capable of being at least partially anodized upon exposure to an electrochemical solution to form a gate structure comprising a gate dielectric adjacent to a gate electrode. In general, the conductive elements **10** and the conductive anodization bus **30** of **FIG. 1** can be any anodizable metal, an alloy of any anodizable metal, a combination of anodizable metals, multilayers of anodizable metals, or combinations thereof. In some embodiments, the plurality of conductive element **10** and the conductive anodization bus **30** may be aluminum, tantalum, niobium, titanium, tungsten, zirconium, hafnium, or combinations thereof. In one embodiment, the plurality of conductive elements **10** and the conductive anodization bus **30** are composed of the same conductive material.

A plurality of conductive elements **10** can be disposed parallel to one another on a substrate **40**, where the substrate **40** is flexible, as illustrated in **FIG. 1** for providing a web **50**. A first conductive element **15** may be parallel to a second conductive element **20**. The first conductive element **15** and at least one second conductive element **20** are electrically connected to the conductive anodization bus **30** providing an electrically conductive path between the conductive elements **10**. The plurality of conductive elements **10** optionally further comprises row contact pads **72** located below the conductive anodization bus **30** of the vertically oriented web **50**. During anodization of the plurality of conductive elements **10**, an optional anodization mask, for example, a photoresist **80**, may be applied to the web **50** to protect the row contact pads **72** and a portion of the conductive elements **10**. That is, the row contact pads **72**, which are used to provide contact to the resulting electronic devices, remain conductive during the anodization process by being protected with the optional photoresist **80**. Plating tape is another example of an anodization mask that can be used to protect a conductive material from anodization. A bus disconnection line **90**, extending orthogonal to the row contact pads **72** and the conductive anodization bus **30,** may be used to separate the conductive anodization bus **30** from the web **50** after manufacture of gate structures. The bus disconnection line **90** may be removed by cutting, etching, laser techniques, or combinations thereof. The at least one second conductive element **20** can be electrically connected to a third conductive element **25** through contact with the conductive anodization bus.

Other configurations of the plurality of conductive elements **10** on a substrate **30** may be envisioned. For example, although **FIG. 1** illustrates the plurality of conductive elements **10** patterned as parallel lines, the conductive elements **10** can have any shape and can be arranged in other configurations.

FIG. 1 further illustrates a web **50**, having a generally vertical orientation, in which a portion of the surface of the plurality of conductive elements **10** on a substrate **40** may not be anodized. In one embodiment, the row contact pads **72** and the conductive anodization bus **30** may be above a surface of an electrochemical solution **120** present in an anodization bath **110** of an anodization station **100** illustrated in **FIG. 2**. In another embodiment, an optional photoresist **80** or plating tape may be used to prevent anodization

of a portion of a surface of the plurality of conductive elements **10** above and below the surface of the electrochemical solution **120** in the anodization bath **110**. For example, the optional photoresist **80** or plating tape can be placed over the row contact pads **72** during anodization.

Referring to **FIG. 2**, a web **50** may begin on a roll as it is delivered with a web delivery roll **70**, and received with a web receiving roll **75**. The web **50** can be pulled from the web delivery roll **70** extending to the web receiving roll **75**. The web **50** passes from the web delivery roll **70** to the web receiving roll **75**. The moving web **50** may provide economy of scale and manufacturing over flat and/or rigid substrates. The web **50** can be moved continuously or can be alternatively moved and held in a stationary position. The web **50** chosen may be capable of unwinding from web delivery roll **70**, and wrapping around the circumference of a web receiving roll **75**, where the web delivery roll **70** and the web receiving roll **75** independently can have a diameter (for example, inner diameter) of up to 50 cm, up to 25 cm, up to 10 cm, up to 5 cm, up to 3 cm, up to 2 cm, or up to 1 cm without distorting or breaking. The force used to wrap the web (for example, a flexible web) **50** around the web receiving roll **75** may be low, such as by unassisted hand, for example, without the aid of levers, machines, hydraulics, and the like. The web **50** may be rolled upon itself. In one embodiment, the web **50** may be sufficiently flexible to be treated in a roll-to-roll process having at least one web delivery roll **70** and at least one web receiving roll **75**.

FIG. 2 illustrates an exemplary top view of a web **50** passing through an exemplary anodization station **100** for anodizing at least a portion of the plurality of conductive elements **10** on a substrate **40** exposed to an electrochemical solution **120** in the anodization bath **110**. The web **50** moves horizontally from the web delivery roll **70** to the web receiving roll **75** having a vertical orientation in a web direction **105**. Web **50** enters the anodization bath **110** at an entry location **113** and exits at an exit location **116** on an opposite side of the anodization bath **110**.

FIG. 2 and **FIG. 3** illustrate an exemplary anodization bath **110** comprising a central tub **102**, a first collection tank **104**, and a second collection tank **106**. The central tub **102** comprises an entrance wall **112** having an entrance slot **117** opening into the first collection tank **104**, and an egress wall **114** comprising an egress slot **115** opening into the

second collection tank **106**. The first collection tank **104** comprises an entry location **113**. The second collection tank **106** comprises an exit location **116**. A web **50** passes through the anodization bath **110** of an anodization station **100**. Pumps (not shown) can be located on the bottom of central tub **102**, the first collection tank **104**, and the second collection tank **106** for pumping an electrochemical solution **120** sufficient to maintain a depth **127** in central tub **102** as illustrated in **FIG. 3**. The central tub **102** comprises the electrochemical solution **120** for anodization of a plurality of conductive elements **10**. The electrochemical solution **120** flows out through the entrance slot **117** and the egress slot **115** of the central tub **102**. The electrochemical solution **120** flowing from the entrance slot **117** and the egress slot **115** can be collected in the first collection tank **104** and the second collection tank **106**, respectively, and pumped back into the central tub **102** as further described in U.S. Patent No. 3,643,670 (Sabatka et al.).

A cathode **130** may have a first edge **185** and a first location **180**. The first location **180** may be located at a first distance **140** from the entrance wall **112** of the central tub **102** of the anodization bath **110**. An optional baffle **400** may be located adjacent to the cathode **130**. The optional baffle **400** may be located between the cathode **130** and the plurality of conductive elements **10** on the substrate **40**. The optional baffle **400** may extend from a first edge **185** to a first location **180**. The plurality of conductive elements **10** can be located between the substrate **40** and the cathode **130**. A web **50** may be located at a fourth distance **210** from the cathode **130** to the plurality of conductive elements **10** on the substrate **40**. The plurality of conductive elements **10** may be located at a second distance **145** from a first side **165** of the central tub **102**. The first side **165** may be parallel to the cathode **130** submerged within the central tub **102**. A voltage can be provided with a power supply **350** attached to both the cathode **130** and an anode **135** that is at least partially within the electrochemical solution **120** to produce an electrical current. **FIG. 2A** illustrates an exemplary anode **135** comprising a conductive anodization bus **30** disposed on a substrate **40**, a plurality of conductive elements **10**, and an anode clamp **302** in contact with the conductive anodization bus **30**.

FIG. 3 illustrates a side view of an exemplary anodization station **100**. Anodization station **100** comprises an anodization bath **110**, an electrochemical solution **120** within the anodization bath **110**, a cathode **130**, an anode **135**, and a power supply

350. The anodization bath **110** comprises a first collection tank **104** having an entry location **113**, a central tub **102**, and a second collection tank **106** having an exit location **116** for a web **50** to pass through in a web direction **105**. The central tub **102** of the anodization bath **110** has sufficient volume to retain the electrochemical solution **120**. The central tub **102** further has a depth **127** sufficient to anodize at least a portion of conductive elements **10** on the substrate **40** of the moving web **50**. In this embodiment, the web **50** is oriented vertically as it passes through the anodization bath **110** in a horizontal direction **105**. The anodization bath **110** comprises an electrochemical solution **120**, wherein at least a portion of the plurality of conductive elements **10** can be exposed to the electrochemical solution **120** in a region extending from the entrance wall **112** to the egress wall **114** of the central tub. The cathode **130** is located within the electrochemical solution **120** of the central tub **102** of the anodization bath **110**. In one embodiment, a portion of the cathode **130** may extend above the surface **122** of the electrochemical solution within the central tub **102**. The cathode **130** can be located at a first distance **140** extending from the entrance wall **112** to a first location **180** of the cathode **130**. The first distance **140** may be sufficient to prevent arcing at the entrance wall **112** by providing a sufficiently low electrical potential in the electrochemical solution **120** at the entrance wall **112**. A third distance **160** determines the cross-web width of the web **50** comprising a plurality of conductive elements **10** below the surface **122** of the electrochemical solution **120** in the central tub **102**.

An electrochemical solution **120** can be used to anodize at least a portion of the surface of a plurality of conductive elements **10** of a web **50** exposed to the electrochemical solution **120**. The electrochemical solution **120** may be commonly referred to as an electrolyte solution. The electrochemical solution **120** may exist as an aqueous solution of acids, bases, salts, or mixtures thereof. Ions or electrolytes of the electrochemical solution **120** conduct electricity in the aqueous solution. An electrical current within the electrochemical solution **120** may result when the individual components of an acid, base or salt dissociate as electrolytes due to the thermodynamic interaction between the solvent (for example, water, alcohols, and combinations thereof) and the solute molecules with the application of a voltage supplied by power supply **350**. Gases may also act as electrolytes under conditions of high temperature or low pressure.

In one embodiment, an electrochemical solution **120** may comprise a carboxylic acid, a salt of a carboxylic acid, or mixtures thereof. For example, the electrochemical solution **120** may comprise tartaric acid, a salt of tartaric acid, or a mixture thereof.

A cathode **130** can have different configurations such as a plate, a rod, a mesh, a screen, or combinations thereof. The material selected for the cathode **130** may be essentially any electronic conductor that is essentially unreactive (for example, inert) in the electrochemical solution **120** contained within the central tub **102** of the anodization bath **110**. The cathode **130** may be attached to a power supply **350** for providing a voltage to an electrochemical solution **120**. Some examples of materials for the cathode **130** may comprise carbon, lead, nickel, stainless steel, platinum, titanium, or combinations thereof. In some embodiments, the cathode **130** comprises stainless steel, platinum, titanium, or combinations thereof.

In one embodiment, a cathode **130** may further comprise an baffle **400** extending from a first edge **185** to a first location **180** of the cathode **130**. The first edge **185** of the cathode is near the entrance wall **112** of the central tub **102**. The baffle **400** may redirect voltage from the cathode **130** to the anode **135** at the entrance wall **112**. The baffle **400** may comprise a nonconductive material. In one embodiment, the baffle **400** comprises polypropylene.

An optional baffle **400** may be submerged within the electrochemical solution **120** of the central tub **102**, or a portion of the optional baffle **400** may be above the surface **122** of the electrochemical solution **120**. In one embodiment, a portion of the optional baffle **400** and a portion of the cathode **130** may be at a distance above the surface **122** of the electrochemical solution **120** within the central tub **102**.

A cathode **130** illustrated in **FIG. 2** and **FIG. 3** may be located at a first distance **140** from the entrance wall **112** of the central tub **102** to a first location **180** of the cathode **130**. The first distance **140** may be sufficient to prevent arcing at the entrance wall **112** of a central tub **102** by providing a sufficiently low electrical potential in the electrochemical solution **120** at the entrance location **112**. Shorting or arcing of electrical current may cause damage to the web and electrodes on the web, may pose harm to humans, and may cause potential damage to equipment and surrounding areas. It is desirable to have an anodization process which provides a low voltage where the web **50** enters at an entrance

slot **117**, and exits at an egress slot **115** of a central tub **102**. Also, the resistivity of the electrochemical solution **120** may be considered in order to limit the local anodization current density, while simultaneously applying a maximum voltage in a region proximate to where the web **50** exits an electrochemical solution **120**. By taking advantage of the resistivity of the electrochemical solution **120**, the appropriate design of the anodization bath **110**, the cathode **130** shape and placement, the areal density of the metal or a plurality of conductive elements **10**, and the speed of the web **50** moving through the anodization bath **110**, a suitable profile of current density and voltage can be developed.

Several parameters for a web **50** may be considered for the placement of a cathode **130** at a first distance **140** from the entrance location **112** of a central tub **102** to reduce possible arcing of the electrical current within the anodization station **100**. Generally, the thickness of the anodic oxide formed during anodization (that is, the thickness of the gate dielectric formed during anodization) is approximately proportional to the applied anodization voltage. The amount of charge required to grow this oxide can be described by an equivalent capacitance, C, where

C = the amount of charge per volt per unit area (mF/cm^2) needed to reach a given anodization voltage. In one embodiment, the equivalent capacitance for aluminum (Al) is approximately 2 mF/cm^2.

The anodization current, I_A (A), can be defined by Formula I, where

$$I_A = AWSVC. \qquad (I)$$

Some of the other parameters of Formula I include:

A = fraction of the area of the web **50** surface (for example, submerged in the electrochemical solution **120**) that comprises a plurality of conductive elements **10** or a metal to be anodized,

W = width (cm) **160** of the web **50** submerged in the electrochemical solution **120**,

S = web **50** speed (cm/s), and

V = anodization voltage (volts) for a power supply **350**.

The anodization current density, that is, the current per unit area, running into the oxide (for example, gate dielectric) formed on the surface of the plurality of conductive elements **10** at a given point, increases approximately exponentially as the first distance

140 from the first location **180** of the cathode **130** becomes smaller. The length scale (cm) of this exponential behavior can be approximated by Formula II:

$$\lambda = D / ASRC. \quad \text{(II)}$$

The parameters of Formula II include:

R = resistivity (ohm-cm) of the electrolyte of the electrochemical solution **120**, and

D = distance (cm) **145** (as shown in **FIG. 2**)from a first side **165** of the central tub **102** of an anodization bath **110**, the first side **165** extending parallel to the surface of the web **50** submerged within the central tub **102** to the plurality of conductive elements **10** on a substrate **40** of the web **50**. Generally, D represents the thickness of the conducting volume of the electrochemical solution **120** in a direction normal to the surface of the web **50**.

If a first distance **140** between the entrance slot **117** of the central tub **102** and the cathode **130** is sufficient, the potential of the electrochemical solution **120** at the entrance slot **117** will be small enough to prevent arcing or a region of unacceptably high anodization current density at the entrance slot **117**. In general, the first distance **140** should be greater than λ (length scale (cm)), greater than 2 λ, or greater than 3 λ.

More generally, the shortest path through the electrochemical solution **120** between the cathode **130** and the entrance slot **117** of the central tub **102** should be greater than λ (cm), greater than 2 λ, or greater than 3 λ. The path can be lengthened by increasing the first distance **140** or including non-conductive baffles, for example, an optional baffle located between the first location **180** of cathode **130** and the entrance wall **112** of a central tub **102**.

The rate of growth or thickening of the oxide layer (for example, gate dielectric) may be proportional to the anodization current density. The electrical field within the oxide layer may not change with the oxide thickness, and may have only a small dependence on current density and temperature. In one embodiment, as the oxide layer grows, the voltage across the oxide layer increases proportionally. In one embodiment, the thickness of the oxide layer/voltage ratio at room temperature may be in a range of 1.2 to 1.5 nanometers per volt (nm/volt). The oxide layer thickness can be generally uniform across the surface of a plurality of conductive elements **10**, since the applied voltage drop

can be essentially uniform in a region of low anodization current density near the egress slot **115** of central tub **102**.

FIG. 3 further illustrates an anodization station **100** having an anodization bath **110** which may be used in a roll-to-roll process for passing through a web **50**. A horizontal conveyer **605** located above the anodization station **100** can support and help move the web **50** through the anodization station **100**. The anodization station **100** can be designed for anodizing a horizontally moving, vertically positioned web **50**.

The anodization bath **110** comprises an entry location **113** at the first collection tank **104**, and an exit location **116** at the second collection tank **106**, which can be vertical slots or openings at opposite ends of the anodization bath **110**. The web **50** can be fed into a first collection tank **104** and passed through an entrance slot **117** of a central tub **102** comprising the electrochemical solution **120**. The web **50** may be passed through the central tub **102** and moved through the egress slot **115** of the central tub **102** into a second collection tank **106**. A plurality of clamps **300** contacts the web **50** being vertically positioned and horizontally unwound at web delivery roll **70** and taken up at web receiving roll **75**. The anode clamps **300** open and close with a clam cam **305**. As the anode clamps **300** approach a pulley **295** above the web delivery roll **70** on a horizontal metal belt **310**, the anode clamps **300** contact the clam cam **305**. The clamp cam **305** opens the anode clamps **300** separating the second contact **380** from the first contact **370** as illustrated in **FIG. 4**. The first contact **370** makes contact with the anodization bus **30**, and the second contact **380** contacts the substrate **40** when the anode clamps **300** attach to the web **50** near the web delivery roll **70** prior to entering the anodization bath **100** at the entry location **113** of the first collection tank **104**. In some embodiments, the first contact **370** and the second contact **380** may both contact an anodization bus **30** located on both sides of a web **50**, such that the web **50** comprises a plurality of conductive elements **10** on both sides of the web **50**. The anode clamps **300** make contact with the conductive anodization bus **30** to complete the electrical circuit for the movement of electrical current sufficient for anodizing at least a portion of the surface of the plurality of conductive elements **10**. The plurality of conductive elements **10** may be exposed at a third distance **160** within the electrochemical solution **120** having a surface **122** and a depth **127** as illustrated in **FIG. 3** and **FIG. 4**. A portion of the surface of the plurality of conductive

elements **10** may not be submerged in the electrochemical solution **120** within the anodization bath **110**. After moving the web **50** through the central tub **102**, the anode clamps **300** release the web **50** upon exiting the anodization bath **110** at the exit location **116** of the second collection tank **106**. After the web **50** leaves the second collection tank **106**, the web **50** may optionally be passed through a rinse station, an air knife, a drying station, or combinations thereof, prior to being passed to the web receiving roll **75**. Before a first clamp of the anode clamps **300** is released from the web **50**, a second clamp is engaged, so that at any time, at least one clamp of the anode clamps **300** is attached to the conductive anodization bus **30**.

An exemplary horizontal conveyer **605** of **FIG. 3** comprises a pulley **295** having a clamp cam **305** for opening and closing the anode clamps **300**. This system is further described in U.S. Patent No. 3,643,670 (Sabatka et al.). The pulley **295** moves the anode clamps **300** along a horizontal conductive metal belt **310**. The horizontal metal belt **310** rests upon glide rolls **320** illustrated in **FIG. 4**. The anode clamps **300** comprise a lifter **315**, a spreader **290**, a spring mechanism **325**, a first contact **370**, and a second contact **380** for attaching and releasing a vertically oriented web **50**. The first contact **370** contacts the anodization bus **30,** and the second contact **380** contacts the substrate **40** of web **50**. The first contact **370** may be rigid, and the second contact **380** may be capable of being moved or displaced during movement of the anode clamps **300** over clamp cam **305**. The pulley **295** maintains contact with the anode clamps **300** connected to the horizontal metal belt **310**.

As the web **50** moves through the anodization bath **110**, a plurality of conductive elements **10** can be anodized. As the web **50** exits the anodization bath **110** at the exit location **116**, the anode clamps **300** release the web **50** to be received with the web receiving roll **75**. With the attachment of at least one clamp of a plurality of anode clamps **300** being attached to the web **50** at a conductive anodization bus **30**, a maximum dispersion of electrical current can be obtained throughout the moving web **50**, where the current density throughout any one anode clamp **300** may be minimized. In one embodiment, the moving web **50** may have a plurality of conductive elements **10** disposed on a substrate **40**, where the plurality of conductive elements **10** may be optionally patterned.

A voltage can be applied using a power supply **350** connected to a cathode **130** and an anode **135** to complete an electrical circuit as illustrated in **FIG. 2** and **FIG. 3**. Upon application of voltage to the electrical circuit, the electrolytes of the electrochemical solution **120** produce an electrical current. A negative charge provided by the power supply **350** enters through the cathode **130**. Typically, a first chemical reaction occurs at the cathode **130** immersed within the electrochemical solution **120**. The electrochemical solution **120** consumes electrons from the cathode **130**, and a second chemical reaction occurs at the anode **135** comprising a portion of the surface of the plurality of conductive elements **10** being exposed to the electrochemical solution **120** producing electrons which can be taken up by the anode **135**. A negative charge cloud develops in the electrochemical solution **120** around the cathode **130**, and a positive charge cloud develops around the anode **135**. The ions of the electrolyte within the electrochemical solution **120** move to neutralize these charges so that the reactions can continue, and the electrons flow. The electrical current generated can result in the oxidation or anodization of the surface of the plurality of conductive elements **10**. A portion of the surface of the plurality of conductive elements **10** can be located outside or above the level of the electrochemical solution **120**, while a portion of the surface of the plurality of conductive elements **10** may be submerged within the anodization bath **110**. Electrochemical solution **120** may be circulated and replenished using recirculation pumps as needed to maintain an appropriate concentration of the electrolytic species.

FIG. 5 illustrates a cross-sectional view of a first conductive element **15** on a substrate **40** prior to anodization. The first conductive element **15** may be illustrative of one of a plurality of conductive elements **10** on a substrate **40** of an exemplary web **50**. The first conductive element **15** as patterned may be oriented parallel to a second conductive element **20**, which may be oriented parallel to a third conductive element **25** as illustrated in **FIG. 1**. Anodization of the conductive element **15** of **FIG. 5** results in the formation of a gate structure **85** as shown in **FIG. 6**.

A gate dielectric **55** may be provided adjacent to a gate electrode **45** as illustrated in **FIG. 6** by a solution anodization process. The gate dielectric **55** may result from anodization of a conductive element **15**, where the conductive element **15** is an inorganic material or an anodizable material. The gate dielectric **55** electrically insulates the gate

electrode **45** under the operating conditions of an electronic device from the balance of the device. The gate dielectric **55** can have a dielectric constant of at least 2, at least 5, at least 10, at least 25, or at least 40. The dielectric constant of the gate dielectric 55 may be up to 150, up to 125, up to 100, or up to 75. The dielectric constant may be in a range of 2 to 150, in a range of 5 to 125, or in a range of 10 to 100.

The first conductive element **15** being deposited and patterned on a substrate **40** of **FIG. 5** can be passed through an anodization station **100** to form an exemplary gate structure **85** of **FIG. 6**. A plurality of conductive elements **10**, such as oxidizable metals may be passed through the anodization station **100** to form a plurality of gate structures **85.**

FIG. 6 illustrates a gate structure **85** comprising a gate dielectric **55** formed adjacent to a gate electrode **45** on a substrate **40**. The gate electrode **45** can be positioned between the gate dielectric **55** and the substrate **40**. The gate dielectric **55** of **FIG. 6** may be a pin-hole free, low leakage, smooth surface which is sufficient as an insulator for an electronic device. The gate dielectric **55** may be achieved by anodization to produce a conformal coating.

At least a portion of the surface of the plurality of conductive elements **10** may be immersed in an electrochemical solution **120** during an anodization process for a period of time sufficient for circulation and agitation of the electrochemical solution **120**. During the immersion of the web **50** within the anodization bath **110**, the anodization solution **120** may reach and wet the surface of the plurality of conductive elements **10** even in areas where the conductive element **15** may be covered by, for example, a small particle. Such penetration by the electrochemical solution **120** may result in a substantially uniform anodization or oxidation of the plurality of conductive elements **10** even in areas where the surface of the conductive element **15** may be covered by a small foreign object such as a small particle.

Consequently, subsequent removal of a particle from the surface of the conductive element **15** may not result in a pinhole in the anodized layer or gate dielectric **55** exposing the conductive element **15**. As a result, an advantage of using a liquid anodization process for oxidizing a conductive element **15** may result in a gate dielectric **55,** where the gate dielectric **55** conforms to the surface profile of the conductive element **15** being anodized

even if in some locations the surface is covered with, for example, small particles forming a conformal coating. In contrast, if the gate dielectric **55** is replaced with a gate dielectric layer that is formed by, for example, vapor depositing a dielectric material onto the conductive element **15**, an area of the conductive element **15** covered by a small particle may not be coated during the deposition process, resulting in the conductive element **15** being exposed in the area after the particle is removed, for example, during further processing.

Another advantage of using an anodization process to form a gate dielectric **55** may be that anodization can result in a substantially uniform insulation of the gate electrode **45** as illustrated in **FIG. 6**. For example, during the anodization process more electrical current tends to flow through an area that is not as anodized, and therefore not as insulating, as the neighboring regions. The additional current intensifies the anodization of the area until the entire anodized region becomes uniformly insulating.

In contrast, in a batch anodization process, a low current density can be achieved by using a power supply operating in a "current source" mode. In this mode, the voltage applied between the cathode and the metal to be anodized may be controlled to provide a desired anodization current density. Initially this voltage may be small, but as the oxide grows, the required voltage gradually increases, until the power supply reaches a desired maximum (or compliance) voltage. Typically, the applied voltage is then held at this value until the anodization current falls to a sufficiently small value.

In another aspect, a process is described for forming a plurality of electronic devices further including both source electrodes and drain electrodes adjacent to a plurality of gate dielectrics. The process includes a semiconductor adjacent to surfaces of both the source electrode and the drain electrode.

FIG. 7 illustrates a cross-section of an embodiment of an exemplary electronic device **510**. A gate electrode **45** is provided on a substrate **40**. A gate structure **85** can result from anodization of a conductive element **15** (**FIG. 5**) to form a gate dielectric **55** adjacent to a gate electrode **45**. A source electrode **72** and a drain electrode **74** are both provided adjacent to a gate dielectric **55**. The source electrode **72** and the drain electrode **74** are both opposite the gate structure **85**. A semiconductor **65** is provided adjacent to a surface of both the source electrode **72** and the drain electrode **74**.

In yet another aspect, a process is described for forming a plurality of electronic devices further including a semiconductor adjacent to a plurality of gate dielectrics. The process provides both a source electrode and a drain electrode adjacent to a surface of the semiconductor opposite the plurality of gate structures. The source electrode is not in contact with the drain electrode.

FIG. 8 illustrates a cross-section of an exemplary electronic device **500**, for example, a thin film transistor (TFT). A gate electrode **45** is provided on a substrate **40**. A gate structure **85** can result from anodization of a conductive element **15** (**FIG. 5**) to form a gate dielectric **55** adjacent to a gate electrode **45**. A semiconductor **65** can be provided adjacent to a gate dielectric **55**. A source electrode **72** and drain electrode **74** may be provided adjacent to a surface of the semiconductor **65** opposite the gate structure **85**. The source electrode **72** does not contact the drain electrode **74**.

FIG. 7 and **FIG. 8** illustrate examples of a gate structure **85** in an electronic device. The gate structure **85** can be extended to a plurality of gate structures **85** which comprise a plurality of gate dielectrics **55** adjacent to a plurality of gate electrodes **45**. The gate structures **85** may be formed from a plurality of conductive elements **10** on a substrate **40**. **FIG. 7** and **FIG. 8** independently represent a plurality of electronic devices **510** and **500**, respectively.

In an electronic device, a voltage can be applied between the gate electrode / source (body) controlling the current flowing between the source and drain electrodes. Common electronic devices include transistors, for example, field effect transistors, arrays of transistors, capacitors, embedded capacitors, diodes, light emitting devices, stacked electronic devices and resistors that are used to form circuits. Electronic devices may include arrays of circuits that perform an electronic function. Examples of arrays or integrated circuits include amplifiers, receivers, transmitters, inverters and oscillators. Applications of these devices and arrays include radio frequency identification devices (RFIDs), smart cards, lamps, displays, and the like. Connections may be made between two or more devices adjacent to each other on the web to form an electrical circuit. In one embodiment, the electronic device is a thin film transistor. In another embodiment, the electronic device is an active matrix display backplane.

A semiconductor (for example, semiconductor layer) is a material whose electrical conductivity can be controlled over a wide range, either permanently or dynamically. The semiconductor layer may comprise inorganic semiconductor materials. Useful inorganic semiconductor materials include amorphous silicon, cadmium sulfide, cadmium selenide, tellurium, zinc oxide, blends, alloys and combinations thereof. Examples of semiconductors may further comprise germanium, gallium arsenide, indium phosphide, silicon germanium, aluminum gallium arsenide, or combinations thereof. In one embodiment, the semiconductor layer may be comprised of zinc oxide, indium zinc oxide, zinc tin oxide, indium gallium zinc oxide, or combinations thereof.

A semiconductor may be provided adjacent to a plurality of gate dielectrics of a plurality of electronic devices as shown in **FIG. 8**. In one embodiment, the semiconductor may be patterned adjacent to the plurality of gate dielectrics. In another embodiment, the semiconductor may be patterned adjacent to a source electrode and a drain electrode as shown in **FIG. 7**. Useful means for application of the semiconductor comprise vapor deposition, solution deposition, spin coating, printing techniques, and combinations thereof.

Source electrodes and drain electrodes may be separated from a gate electrode by a gate dielectric as shown in **FIG. 7**. In one embodiment, the source and drain electrode may be separated by a semiconductor adjacent to a gate dielectric as shown in **FIG. 8**. The source and drain electrodes can be a conductive material. Useful materials may include those similarly described for the conductive elements. For example, source electrode and drain electrodes may include aluminum, barium, calcium, chromium, copper, gold, silver, nickel, palladium, platinum, titanium, alloys, multilayers, and combinations thereof. In one embodiment, the source electrode and the drain electrode both comprise aluminum, gold, copper, silver, titanium, chromium, metal oxides, doped semiconductors, or combinations thereof. Useful means for application of the source electrodes and drain electrodes may comprise vapor deposition, solution deposition, spin coating, printing techniques, and combinations thereof.

In one aspect, a process is provided for forming a plurality of gate structures. A web is provided that comprises a substrate, a plurality of conductive elements disposed on the substrate, and a conductive anodization bus. The conductive anodization bus is

adjacent to a first edge of the substrate. A first conductive element and at least one second conductive elements are electrically connected to the conductive anodization bus. The web is moving, where the web is delivered with a web delivery roll and received with a web receiving roll. The web extends from the web delivery roll to the web receiving roll, and the web passes from the web delivery roll to the web receiving roll. The web passes through an anodization station. The anodization station comprises a anodization bath having an entry location and an exit location for the web; an electrochemical solution retained within the anodization bath, wherein the electrochemical solution has a surface; a cathode located within the electrochemical solution where the plurality of conductive elements is positioned between the substrate and the cathode; an anode; and a power supply attached to the anode and the cathode. The cathode may be located at a distance from the entry location, where the distance is sufficient to prevent arcing at the entry location by providing a sufficiently low electrical potential in the electrochemical solution at the entry location. The anode comprises the conductive anodization bus positioned above the surface of the electrochemical solution; a plurality of conductive elements where at least a portion of the plurality of the conductive elements are positioned below the surface of the electrochemical solution; and a plurality of clamps, where at least one clamp is in electrical contact with the conductive anodization bus. At least a portion of the surface of the plurality of conductive elements exposed to the electrochemical solution is anodized to form a plurality of gate structures. The plurality of gate structures comprises a plurality of gate dielectrics adjacent to a plurality of gate electrodes. The plurality of gate electrodes is positioned between the plurality of gate dielectrics and the substrate.

In another aspect, a process is provided for forming a plurality of electronic devices. A web is provided that comprises a substrate, a plurality of conductive elements disposed on the substrate, and a conductive anodization bus. The conductive anodization bus is adjacent to a first edge of the substrate. A first conductive element and at least one second conductive elements are electrically connected to the conductive anodization bus. The web is moving, where the web is delivered with a web delivery roll and received with a web receiving roll. The web extends from the web delivery roll to the web receiving roll, and the web passes from the web delivery roll to the web receiving roll. The web passes through an anodization station. The anodization station comprises an anodization bath having an entry location and an exit location for the web; an electrochemical solution

retained within the anodization bath, wherein the electrochemical solution has a surface; a cathode located within the electrochemical solution where the plurality of conductive elements is positioned between the substrate and the cathode; an anode; and a power supply attached to the anode and the cathode. The cathode may be located at a distance from the entry location, where the distance is sufficient to prevent arcing at the entry location by providing a sufficiently low electrical potential in the electrochemical solution at the entry location. The anode comprises the conductive anodization bus positioned above the surface of the electrochemical solution; a plurality of conductive elements where at least a portion of the plurality of the conductive elements are positioned below the surface of the electrochemical solution; and a plurality of clamps, where at least one clamp is in electrical contact with the conductive anodization bus. At least a portion of the surface of the plurality of conductive elements exposed to the electrochemical solution is anodized to form a plurality of gate structures. The plurality of gate structures comprises a plurality of gate dielectrics adjacent to a plurality of gate electrodes. The plurality of gate electrodes is positioned between the plurality of gate dielectrics and the substrate. The process further comprises providing a semiconductor adjacent to the plurality of gate dielectrics. A source electrode and a drain electrode are both provided adjacent to the surface of the semiconductor opposite the plurality of gate structures, where the source electrode is not in contact with the drain electrode.

In another aspect, a process is provided for forming a plurality of electronic devices. A web is provided that comprises a substrate, a plurality of conductive elements disposed on the substrate, and a conductive anodization bus. The conductive anodization bus is adjacent to a first edge of the substrate. A first conductive element and at least one second conductive elements are electrically connected to the conductive anodization bus. The web is moving, where the web is delivered with a web delivery roll and received with a web receiving roll. The web extends from the web delivery roll to the web receiving roll, and the web passes from the web delivery roll to the web receiving roll. The web passes through an anodization station. The anodization station comprises a anodization bath having an entry location and an exit location for the web; an electrochemical solution retained within the anodization bath, wherein the electrochemical solution has a surface; a cathode located within the electrochemical solution where the plurality of conductive elements is positioned between the substrate and the cathode; an anode; and a power

supply attached to the anode and the cathode. The cathode may be located at a distance from the entry location, where the distance is sufficient to prevent arcing at the entry location by providing a sufficiently low electrical potential in the electrochemical solution at the entry location. The anode comprises the conductive anodization bus positioned above the surface of the electrochemical solution; a plurality of conductive elements where at least a portion of the plurality of the conductive elements are positioned below the surface of the electrochemical solution; and a plurality of clamps, where at least one clamp is in electrical contact with the conductive anodization bus. At least a portion of the surface of the plurality of conductive elements exposed to the electrochemical solution is anodized to form a plurality of gate structures. The plurality of gate structures comprises a plurality of gate dielectrics adjacent to a plurality of gate electrodes. The plurality of gate electrodes is positioned between the plurality of gate dielectrics and the substrate. The process further comprises providing both a source electrode and a drain electrode adjacent to the plurality of gate dielectrics. A semiconductor is provided adjacent to the surface of both the source electrode and the drain electrode opposite the plurality of gate structures, where the source electrode is not in contact with the drain electrode.

The disclosure will be further clarified by the following examples which are exemplary and not intended to limit the scope of the disclosure.

Examples

Unless otherwise noted, all parts, percentages, and ratios reported in the following examples are on a weight basis, and all reagents used in the examples were obtained, or are available, from the chemical suppliers described below, or may be synthesized by conventional techniques.

Example 1

Aluminum (Al) was sputtered and patterned on polyethylene-2,6-napthalate ((PEN), 100 micron (μm), Dupont Teijin Films, Japan)) as a substrate, to form a plurality of conductive elements. A web comprises the substrate, conductive elements disposed on the substrate, and a conductive anodization bus parallel to a first edge of the substrate. The plurality of conductive elements was anodized by moving the web through an anodization station. The patterned aluminum conductive elements were anodized as the web was moved through an anodization station.

Prior to deposition of the Al metal, the substrate was degassed with an infrared (IR) tube heater at a web speed of 2.4 meters/minute (m/min). An adhesion layer of 3 nanometer (nm) SiO_x was radio frequency (RF) sputtered on the substrate with a 12.7 cm x 38.1 cm planar magnetron SiO_2 sputtering target (Angstrom Sciences, Duquesne, PA) at a power of 1 kilowatt (kW) and 13.56 megahertz (MHz) having a web speed of 0.305 m/min. The chamber background pressure was 10 millitorr (mTorr) having an argon (Ar) gas flow of 600 standard cubic centimeters (sccm) and an oxygen (O_2) gas flow of 7.5 sccm.

Subsequently, 200 nm of aluminum metal was sputtered on the substrate at a web speed of 1.219 m/min. The Al metal was sputtered with a 12.7 cm x 38.1 cm planar magnetron sputtering target (Angstrom Sciences, Duquesne, PA) having a purity of 99.999 % at a DC power of 9 kW. The background chamber pressure was 5 mTorr, with an argon gas flow of 600 sccm. All three steps (degas, SiO_x adhesion layer deposition and Al metal deposition) were done sequentially in a single multi-purpose vacuum coater in one vacuum pump down.

The continuous aluminum layer on a substrate was patterned with negative dry film photoresist (DFPR) using photolithography methods. A 175 micron (μm) dry film photoresist (UGH-072, Asahi Kasei, Japan) was laminated on the aluminum layer coated on the PEN at 206.8 kiloPascal (kPa)), at a temperature of 110 °C at a roll speed of 0.914 m/min. The film was exposed at 100 millijoules (mJ) with a step and repeat exposure unit to a chrome on quartz photomask (Infinite Graphics, Minneapolis, MN). Step and repeat exposure units are known in the art. An ORC step and repeat exposure unit known as the Proform 3500 is available from DRC Imaging Corporation of City of Industry, CA. A similar step and repeat exposure unit was used. The DFPR release layer was removed and the DFPR was developed with sodium carbonate ((Na_2CO_3), Sigma Aldrich, St. Louis, MO) solution with a spray pressure of 27.6 kilopascals (kPa), a temperature of 21 °C at a web speed of 1.524 m/min. The DFPR was baked at 35 °C having a web speed of 1.829 m/min. The aluminum metal was etched with 45 wt. % KOH (Sigma Aldrich, St. Louis, MO) at 27.6 °C. The DFPR was removed with 4.61 wt. % monoethanolamine ((MEA), Sigma Aldrich, St. Louis, MO) at 40 °C, and the substrate was rinsed with deionized (DI) water at 32 °C. The Al metal etch, DFPR removal and rinse steps were all done inline at a web speed of 2.234 m/min. The web was then cleaned with a liquinox (2 weight (wt.) %,

Sigma Aldrich, St. Louis, MO) / citric acid (2 wt. %, Sigma Aldrich, St. Louis, MO) solution at 120 48.9 °C at a web speed of 0.457 m/min.

The patterned conductive elements were anodized in an anodization station. The station comprises a central tub having a length of 0.914 m, a stainless steel cathode, and a polypropylene baffle. The cathode was approximately 30.54 cm in height, and extended about 65 cm in length parallel to the web. The baffle was located adjacent to the front edge of the cathode. The baffle was about 30.54 cm in height, about 0.70 cm in thickness, and about 20 cm in length. A portion of both the cathode and the baffle extended about 5 cm about the surface of the electrochemical solution. The web was held in a vertical configuration, with anode clamps attaching to the conductive anodization bus for the anode every 14 cm on the web. The potential was set to 75 volts (V) with a maximum allowable current setting of 150 milliamps (mA) and the web speed was 0.076 m/min. The measured current was in the range of 75 - 110 mA. The electrochemical solution for anodization consisted of a 4:1 (by weight) mixture of ethylene glycol (Sigma Aldrich; St. Louis, MO) and 3 wt % tartaric acid (Sigma Aldrich, St. Louis, MO) in a deionized water solution that was titrated to a pH of 5.5 with ammonium hydroxide ((NH_4OH), Sigma Aldrich, St. Louis, MO). The rate of oxide formation for the gate dielectric at room temperature was between 1.2-1.5 nm/V. Samples anodized at a voltage of 75 V produced approximately 980 angstroms (Å) of anodized Al_2O_3.

The thickness and quality of the anodized Al_2O_3 gate dielectric adjacent to the gate electrode for forming a gate structure was tested by measuring the leakage of the capacitor structures. Gold top contacts (60 nm) were deposited on the patterned gate electrode and gate dielectric in a vacuum evaporator (CVC Products) through shadow-masks. The top contacts were 6nm gold circles having diameters of 1 mm, 2mm, and 5 mm. The current/voltage characteristics were measured with an electrometer (Keithley 2400, Keithley Instruments, Inc., Cleveland, OH) in a constant voltage mode. The measured capacitance was 750 picofarads/square millimeter (pF/mm^2), and the calculated thickness of the anodized gate dielectric was approximately 100 nm.

Example 2

Thin film transistors were fabricated using the gate structures made using an anodization process of Example 1. The substrate was degassed with an IR tube heater and 3 nm of SiO_x and 200 nm of Al was sputtered under the same conditions and using the

same equipment as the conductive metal deposition. The source and drain electrodes were patterned in the same manner as the conductive metal using DFPR (UGH-072, Asahi Kasei, Japan). The conductive metal was patterned using a photomask aligner and exposed at 100 mJ. The DFPR release layer was removed and the DPFR was developed with a sodium carbonate ((Na_2CO_3), Sigma Aldrich, St. Louis, MO) solution with a spray pressure of 27.57 kPa, a temperature of 21.1 °C at a web speed of 152.4 m/min. The DFPR was baked at 100 °C at a web speed of 1.82 m/min. The conductive metal was etched with 45 wt. % potassium hydroxide ((KOH), Sigma-Aldrich, St. Louis, MO) at 26.7 °C. The DFPR was removed with 4.61 wt. % monoethanolamine ((MEA), Sigma Aldrich, St. Louis, MO) at 40 °C and the web was rinsed with deionized water at 32.2 °C. The Al metal etch, DFPR removal and rinse steps were all done inline at a web speed of 2.29 m/min. The web was then cleaned with a liquinox (2 wt. %, Sigma Aldrich, St. Louis, MO) / citric acid (2 wt. %, Sigma Aldrich, St. Louis, MO) solution at 48.9 °C at a speed of 0.457 m/min.

The web was degassed by passing in front of an IR tube heater four times at 2.438 m/min prior to the deposition of a zinc oxide (ZnO) semiconductor. Zinc oxide was sputtered from a ZnO sputtering target (Angstrom Sciences, Duquesne, PA) using three passes at 0.305 m/min at a RF power of 1 kW. The chamber pressure was 5 mTorr and the O_2 gas was 4 sccm, 6 sccm and 8 sccm with 600 sccm of Ar.

The semiconductor layer was patterned in the same fashion as the conductive elements and the source and drain electrodes using DFPR (UGH-072, Asahi Kasei, Japan), and exposed at 100 mJ with a photomask aligner (Infinite Graphics, Minneapolis, MN). The DFPR was exposed using an ORC step and repeat exposure unit (DRC Imaging Corporation, City of Industry, CA) utilizing edge fiducials for alignment, and developed with sodium carbonate ((Na_2CO_3), Sigma Aldrich, St. Louis, MO) Zinc oxide (ZnO) was etched with a CAN (Cyantek CR-4S, Syntec, Inc., San Jose, CA) etch (Cyantek CR-4S was diluted to 40 % volume/volume, resulting in a Ce(IV) concentration = 0.064 N and a HNO_3 concentration = 58g/L) at room temperature having a web speed of 0.437m /min. The DPFR was left on the devices and not removed.

Devices on samples implementing three different ZnO deposition conditions (4 sccm O_2, 6 sccm O_2, and 8 sccm O_2) were examined after roll-to-roll patterning. The thin film transistors on the 4 sccm O_2 samples were baked for 10 minutes at 115 °C. Some of

the devices had a mobility of ~ 0.4 cm^2/V-s; $I_{on/off}$ (current) ~ 10^6, S (voltage decay) ~ 2 V/decade, and V_t (voltage)~ 8 V. The TFTs (thin film transistors) on the 6 sccm O_2 samples did not require a bake and had device characteristics that were similar to the 4 sccm O_2 samples. The 8 sccm O_2 samples did not require a bake, but were more resistive in operation. The devices having a demonstrated transistor behavior had a mobility of ~0.001 cm^2/V-s.

Various modifications and alterations of this disclosure will be apparent to those skilled in the art without departing from the scope and spirit of this disclosure, and it should be understood that this disclosure is not limited to the illustrative elements set forth herein.

What is claimed is:

1. A process for forming a plurality of gate structures, the process comprising:

providing a substrate comprising (a) a backing, (b) a plurality of conductive elements disposed on the backing, and (c) a conductive anodization bus parallel to a first edge of the backing, wherein a first conductive element and at least one second conductive element are electrically connected to the anodization bus;

moving the substrate, wherein the substrate is delivered with a substrate delivery roll and received with a substrate receiving roll, the substrate extends from the substrate delivery roll to the substrate receiving roll, and the substrate passes from the substrate delivery roll to the substrate receiving roll;

passing the substrate through an anodization station, the anodization station comprising (a) an anodization bath comprising an entry location and an exit location for the substrate, (b) an electrochemical solution retained within the anodization bath, wherein the electrochemical solution has a surface, (c) a cathode located within the electrochemical solution, the plurality of conductive elements positioned between the backing and the cathode, (d) an anode comprising (i) the anodization bus, wherein the anodization bus is positioned above the surface of the electrochemical solution, (ii) the plurality of conductive elements, wherein at least a portion of the plurality of conductive elements are positioned below the surface of the electrochemical solution, and (iii) a plurality of clamps, wherein at least one clamp is in electrical contact with the anodization bus, and (e) a power supply attached to the anode and the cathode; and

anodizing at least a portion of the surface of the plurality of conductive elements exposed to the electrochemical solution to form a plurality of gate structures comprising a plurality of gate dielectrics adjacent to a plurality of gate electrodes, the plurality of gate electrodes positioned between the plurality of gate dielectrics and the backing.

2. The process of claim 1, wherein the backing comprises a metal, metal alloy, polyester, polyimide, polyetherimide, liquid crystal polymer, polycarbonate, or combinations thereof.

3. The process of claim 1, wherein the plurality of conductive elements comprises aluminum, tantalum, niobium, zirconium, tungsten, titanium, hafnium, or combinations thereof.

4. The process of claim 1, further comprising a horizontal conveyor to support and move the substrate passing through the anodization station, the horizontal conveyor mounted above the substrate and moving in a plane parallel to a substrate oriented in a vertical plane passing through the anodization bath, wherein the plurality of clamps are mounted to move with the horizontal conveyor.

5. The process of claim 4, wherein the plurality of clamps are aligned with the substrate, the at least one clamp (a) attaching to the anodization bus of the substrate prior to the entry location, (b) moving the substrate through the anodization bath, and (c) releasing the substrate after the exit location, wherein the horizontal conveyor comprises a clamp cam for independently opening and closing the at least one clamp.

6. A process for forming a plurality of electronic devices, the process comprising:

providing a substrate comprising (a) a backing, (b) a plurality of conductive elements disposed on the backing, and (c) a conductive anodization bus parallel to a first edge of the backing, wherein a first conductive element and at least one second conductive element are electrically connected to the anodization bus;

moving the substrate, wherein the substrate is delivered with a substrate delivery roll and received with a substrate receiving roll, the substrate extends from the substrate delivery roll to the substrate receiving roll, and the substrate passes from the substrate delivery roll to the substrate receiving roll;

passing the substrate through an anodization station, the anodization station comprising (a) an anodization bath comprising an entry location and an exit location for the substrate, (b) an electrochemical solution retained within the anodization bath, wherein the electrochemical solution has a surface, (c) a cathode located within the electrochemical solution, the plurality of conductive elements

positioned between the backing and the cathode, (d) an anode comprising (i) the anodization bus, wherein the anodization bus is positioned above the surface of the electrochemical solution, (ii) the plurality of conductive elements, wherein at least a portion of the plurality of conductive elements are positioned below the surface of the electrochemical solution, and (iii) a plurality of clamps, wherein at least one clamp is in electrical contact with the anodization bus, and (e) a power supply attached to the anode and the cathode;

anodizing at least a portion of the surface of the plurality of conductive elements exposed to the electrochemical solution to form a plurality of gate structures comprising a plurality of gate dielectrics adjacent to a plurality of gate electrodes, the plurality of gate electrodes positioned between the plurality of gate dielectrics and the backing;

providing a semiconductor adjacent to the plurality of gate dielectrics; and

providing both a source electrode and a drain electrode adjacent to a surface of the semiconductor opposite the plurality of gate structures, wherein the source electrode is not in contact with the drain electrode.

7. The process of claim 6, wherein the electronic device is a thin film transistor.

8. The process of claim 6, wherein the electronic device is an active matrix display backplane.

9. The process of claim 6, wherein the semiconductor is inorganic.

10. The process of claim 6, further comprising patterning the semiconductor adjacent to the plurality of gate dielectrics.

11. The process of claim 6, wherein the semiconductor comprises zinc oxide, indium zinc oxide, zinc tin oxide, indium gallium zinc oxide, or combinations thereof.

12. The process of claim 6, wherein both the source electrode and the drain electrode comprise aluminum, gold, copper, silver, titanium, chromium, metal oxides, doped semiconductors, or combinations thereof.

13. A process for forming a plurality of electronic devices, the process comprising:

providing a substrate comprising (a) a backing, (b) a plurality of conductive elements disposed on the backing, and (c) a conductive anodization bus parallel to a first edge of the backing, wherein a first conductive element and at least one second conductive element are electrically connected to the anodization bus;

moving the substrate, wherein the substrate is delivered with a substrate delivery roll and received with a substrate receiving roll, the substrate extends from the substrate delivery roll to the substrate receiving roll, and the substrate passes from the substrate delivery roll to the substrate receiving roll;

passing the substrate through an anodization station, the anodization station comprising (a) an anodization bath comprising an entry location and an exit location for the substrate, (b) an electrochemical solution retained within the anodization bath, wherein the electrochemical solution has a surface, (c) a cathode located within the electrochemical solution, the plurality of conductive elements positioned between the backing and the cathode, (d) an anode comprising (i) the anodization bus, wherein the anodization bus is positioned above the surface of the electrochemical solution, (ii) the plurality of conductive elements, wherein at least a portion of the plurality of conductive elements are positioned below the surface of the electrochemical solution, and (iii) a plurality of clamps, wherein at least one clamp is in electrical contact with the anodization bus, and (e) a power supply attached to the anode and the cathode;

anodizing at least a portion of the surface of the plurality of conductive elements exposed to the electrochemical solution to form a plurality of gate structures comprising a plurality of gate dielectrics adjacent to a plurality of gate electrodes, the plurality of gate electrodes positioned between the plurality of gate dielectrics and the backing;

providing both a source electrode and a drain electrode adjacent to the plurality of gate dielectrics, wherein the source electrode is not in contact with the drain electrode; and

providing a semiconductor adjacent to a surface of both the source electrode and the drain electrode, both the source electrode and the drain electrode opposite the plurality of gate.

14. The process of claim 13, wherein the electronic device is a thin film transistor.

15. The process of claim 13, wherein the electronic device is an active matrix display backplane.

16. The process of claim 13, wherein the semiconductor is inorganic.

17. The process of claim 13, further comprising patterning the semiconductor adjacent to the source electrode and the drain electrode.

18. The process of claim 13, wherein the semiconductor comprises zinc oxide, indium zinc oxide, zinc tin oxide, indium gallium zinc oxide, or combinations thereof.

19. The process of claim 13, wherein both the source electrode and the drain electrode comprise aluminum, gold, copper, silver, titanium, chromium, metal oxides, doped semiconductors, or combinations thereof.

20. A process for forming a plurality of gate structures, the process comprising:

providing a substrate comprising (a) a backing, (b) a plurality of conductive elements disposed on the backing, and (c) a conductive anodization bus parallel to a first edge of the backing, wherein a first conductive element and at least one second conductive element are electrically connected to the anodization bus;

moving the substrate, wherein the substrate is delivered with a substrate delivery roll and received with a substrate receiving roll, the substrate extends from the substrate delivery roll to the substrate receiving roll, and the substrate passes from the substrate delivery roll to the substrate receiving roll;

passing the substrate through an anodization station, the anodization station comprising (a) an anodization bath comprising an entry location and an exit location for the substrate, (b) an electrochemical solution retained within the anodization bath, wherein the electrochemical solution has a surface, (c) a cathode located within the electrochemical solution, the cathode located at a distance from the entry location, the distance being sufficient to prevent arcing at the entry location, wherein the plurality of conductive elements is positioned between the backing and the cathode, (d) an anode comprising (i) the anodization bus, wherein the anodization bus is positioned above the surface of the electrochemical solution, (ii) the plurality of conductive elements, wherein at least a portion of the plurality of conductive elements are positioned below the surface of the electrochemical solution, and (iii) a plurality of clamps, wherein at least one clamp is in electrical contact with the anodization bus, and (e) a power supply attached to the anode and the cathode; and

anodizing at least a portion of the surface of the plurality of conductive elements exposed to the electrochemical solution to form a plurality of gate structures comprising a plurality of gate dielectrics adjacent to a plurality of gate electrodes, the plurality of gate electrodes positioned between the plurality of gate dielectrics and the backing.

21. A process for forming a plurality of electronic devices, the process comprising:

providing a substrate comprising (a) a backing, (b) a plurality of conductive elements disposed on the backing, and (c) a conductive anodization bus parallel to a first edge of the backing, wherein a first conductive element and at least one second conductive element are electrically connected to the anodization bus;

moving the substrate, wherein the substrate is delivered with a substrate delivery roll and received with a substrate receiving roll, the substrate extends from the substrate delivery roll to the substrate receiving roll, and the substrate passes from the substrate delivery roll to the substrate receiving roll;

passing the substrate through an anodization station, the anodization station comprising (a) an anodization bath comprising an entry location and an exit location for the substrate, (b) an electrochemical solution retained within the anodization bath, wherein the electrochemical solution has a surface, (c) a cathode located within the electrochemical solution, the cathode located at a distance from the entry location, the distance being sufficient to prevent arcing at the entry location, wherein the plurality of conductive elements is positioned between the backing and the cathode, (d) an anode comprising (i) the anodization bus, wherein the anodization bus is positioned above the surface of the electrochemical solution, (ii) the plurality of conductive elements, wherein at least a portion of the plurality of conductive elements are positioned below the surface of the electrochemical solution, and (iii) a plurality of clamps, wherein at least one clamp is in electrical contact with the anodization bus, and (e) a power supply attached to the anode and the cathode;

anodizing at least a portion of the surface of the plurality of conductive elements exposed to the electrochemical solution to form a plurality of gate structures comprising a plurality of gate dielectrics adjacent to a plurality of gate electrodes, the plurality of gate electrodes positioned between the plurality of gate dielectrics and the backing;

providing a semiconductor adjacent to the plurality of gate dielectrics; and

providing both a source electrode and a drain electrode adjacent to a surface of the semiconductor opposite the plurality of gate structures, wherein the source electrode is not in contact with the drain electrode.

22. A process for forming a plurality of electronic devices, the process comprising:

providing a substrate comprising (a) a backing, (b) a plurality of conductive elements disposed on the backing, and (c) a conductive anodization bus parallel to a first edge of the backing, wherein a first conductive element and at least one second conductive element are electrically connected to the anodization bus;

moving the substrate, wherein the substrate is delivered with a substrate delivery roll and received with a substrate receiving roll, the substrate extends from the substrate delivery roll to the substrate receiving roll, and the substrate passes from the substrate delivery roll to the substrate receiving roll;

passing the substrate through an anodization station, the anodization station comprising (a) an anodization bath comprising an entry location and an exit location for the substrate, (b) an electrochemical solution retained within the anodization bath, wherein the electrochemical solution has a surface, (c) a cathode located within the electrochemical solution, the cathode located at a distance from the entry location, the distance being sufficient to prevent arcing at the entry location, wherein the plurality of conductive elements is positioned between the backing and the cathode, (d) an anode comprising (i) the anodization bus, wherein the anodization bus is positioned above the surface of the electrochemical solution, (ii) the plurality of conductive elements, wherein at least a portion of the plurality of conductive elements are positioned below the surface of the electrochemical solution, and (iii) a plurality of clamps, wherein at least one clamp is in electrical contact with the anodization bus, and (e) a power supply attached to the anode and the cathode;

anodizing at least a portion of the surface of the plurality of conductive elements exposed to the electrochemical solution to form a plurality of gate structures comprising a plurality of gate dielectrics adjacent to a plurality of gate electrodes, the plurality of gate electrodes positioned between the plurality of gate dielectrics and the backing;

providing both a source electrode and a drain electrode adjacent to the plurality of gate dielectrics, wherein the source electrode is not in contact with the drain electrode; and

providing a semiconductor adjacent to a surface of both the source electrode and the drain electrode, both the source electrode and the drain electrode opposite the plurality of gate.