DETAILED DESCRIPTION

[0010] Figure 1 is a flow diagram summarizing a method 100 according to at least one embodiment. The methods of Figure 1 may be used to increase the crystallinity or crystal grain size of a semiconductor material. Semiconductor materials for which the methods described herein may be used include elemental semiconductors such as silicon and germanium, combinations of elemental semiconductors, such as various formulations of silicon-germanium (Si_xGe_y), and compound semiconductors such as Group III/V semiconductors and Group II/VI semiconductors. Examples of compound semiconductors that may benefit from the methods described herein include, but are not limited to, CIGS materials, gallium arsenide, indium gallium arsenide, indium phosphide, indium antimonide, indium aluminum gallium arsenide, gallium phosphide, zinc telluride, gallium/aluminum/indium nitrides, silicon carbide, and other similar combinations.

[0011] A substrate of any of the materials mentioned above is disposed in an energy device operable to deliver pulsed laser energy, or other types of pulsed energy such as flash lamp or electron beam energy, to the substrate. At 102, the substrate is exposed to pulsed laser energy to melt a first treatment area of the substrate. A single pulse of laser energy may suffice in some cases, but two or more pulses may be delivered in other cases. In cases where a single pulse is used to melt the treatment area, the ambient temperature of the substrate may be increased to reduce thermal stresses from rapid heating of the treatment area. The elevated ambient is typically less than about 500°C, such less than about 400°C, for example between about 100°C and about 400°C. In some embodiments, the ambient temperature may be room temperature or below.

[0012] Characteristics of the pulsed laser energy, such as fluence and duration are selected to melt the treatment area. Typically, energy content delivered to melt the treatment area is just below an amount of energy that would ablate the substrate surface. In one embodiment, two pulses of 532 nm laser light from a frequency-doubled Nd:YAG laser, each pulse having fluence of about 0.45 J/cm^2 and duration of about 26 nsec., separated by a duration of about 31 nsec., may be

used to melt a portion of a silicon substrate. In some cases, a pulse train may be used to melt the treatment area.

[0013] At 104, at least a portion of the treatment area is resolidified to form a large crystal portion and a small crystal portion. The resolidification may be initiated by contact between the melt phase and a crystalline seed. As the temperature near the crystalline seed drops to near the freezing point of the liquid material, a freeze front begins to propagate through the treatment area as a surface that is articulated in three-dimensions. The rate at which the freeze front propagates is typically about 10-30 m/sec, limited by rate of heat removal from the melt phase into the bulk of the substrate, which is therefore enhanced by maintaining the substrate at a lower ambient temperature.

[0014] The ambient temperature at which the substrate is most beneficially maintained depends on the material being processed. Many of the temperatures described herein are relevant to silicon, doped silicon, and alloys that are mostly silicon, but it should be understood that other temperatures will be relevant to other materials. Copper and germanium, for example, have similar melting points that are lower than silicon, and compound semiconductors containing gallium may have dramatically lower melting points than silicon. Silicon carbide, on the other hand, has a melting point higher than silicon. Moreover, the different materials have different thermal conductivities and thermal heat capacitites, or specific heat capacities, that influence cooling rates. Gallium arsenide, for example, is a relatively poor thermal conductor, so a lower ambient relative to its melting point may be beneficial for crystallizing gallium arsenide. Thus, room temperature substrate ambients, or ambients below room temperature, may be desired for some embodiments, while higher ambients may be useful for others.

[0015] The process of freezing typically proceeds faster than the process of crystal formation, a disparity that is intensified by large temperature difference between the melt phase and the solid phase. As the freeze front progresses, a large crystal area develops up to a first distance from the seed material, and a

small crystal area develops to a second distance further from the seed material than the first distance. In most prior art processes, the temperature difference between the melt phase and the solid phase is managed by maintaining the substrate at an elevated ambient temperature to reduce the rate of heat removal from the melt phase. The inventors have discovered that by delivering pulses of energy having a duration and energy content selected to deliver an appropriate amount of energy to the freeze front and the small crystal area, the temperature difference between the small crystal area and the melt phase can be reduced by preferentially heating the small crystal area, and the rates of crystallization and freezing more nearly matched. By delivering an energy pulse with appropriate characteristics to the freeze front, it is possible to perform large crystal recrystallization at virtually any ambient substrate temperature quickly.

[0016] At 106, a laser pulse is delivered to the treatment area. The laser pulse, which may be a freeze control pulse, may melt the small crystal area, or the laser pulse may preferentially raise the temperature of the small crystal area to a temperature close to the temperature of the melt phase, for example within about 10°C of the melt phase temperature. The laser pulse has an energy content and duration selected based on the mass of the small crystal area developed during the resolidification of 104. The duration is selected such that power delivery to the substrate is most efficient. Power delivery that is above an efficient zone results in reflection of substantial power from the substrate and/or damage to the substrate.

[0017] The energy content delivered by the laser pulse is selected to increase the temperature of the small crystal area to a temperature near the melt temperature. The temperature may be just above or just below the melt temperature, such that the small crystal area, or a portion thereof, melts or nearly melts. The energy content of the laser pulse may be selected to melt a desired fraction of the small crystal area while providing energy to convert the rest of the small crystal area to large crystals. Depending on the ambient substrate temperature, the small crystal area will have a temperature gradient from near the melt temperature adjacent to the liquid area to a lower temperature far from the

beam. Maintaining the substrate near room temperature after alignment reduces the possibility of alignment drift due to thermal expansion effects. Alternately, the substrate may be heated to reduce the overall energy signature of the process. In most embodiments, the substrate ambient will be maintained at less than about 200°C.

[0024] A first die of the amorphous layer is identified for treatment, and the substrate positioned such that the first treatment die is aligned with the laser source, for example by moving the work surface according to an x-y positioning control. The first treatment die is an area of the amorphous layer formed over a crystalline silicon seed. A first laser pulse having fluence of 0.45 J/cm^2 and duration of 26 nsec is delivered to the first treatment die. After a rest duration of 31 nsec, a second laser pulse having the same fluence and duration is delivered to the first treatment die. The two laser pulses substantially melt the amorphous silicon material without melting the crystalline seed.

[0025] The molten silicon is allowed to freeze for a first freeze duration of 700 nsec. A third laser pulse having the same fluence and duration is then delivered to the first treatment die. The third laser pulse thermally treats any small crystals that grow in the molten silicon, driving them to convert to large crystals. The molten silicon is then allowed to freeze for a second freeze duration of 1200 nsec. A fourth laser pulse having reduced fluence of 0.26 J/cm^2 and the same duration as the prior pulses, is delivered to the first treatment die. The fourth laser pulse completes conversion of the first treatment die to large crystal silicon.

[0026] The substrate is then moved to target an adjacent die for treatment, and the process is repeated. If the adjacent die does not contain a crystalline seed, contact with the prior treated die serves to seed crystallization. In this way, the entire amorphous layer may be converted to large crystal silicon.

[0027] The method 100 is described using freeze periods at 104 and 108 that result in formation of large grain crystals and small grain crystals, with laser pulses delivered to convert the small grain crystals into large grain crystals. In other

with each of the energy generators 202A-D of the energy source 202. In the embodiment of Figure 2, each of the energy generators 202A-D is a pumped q-switched laser, and the controller has an electronic timer that communicates electrically with the q-switch of each laser to control pulse delivery. Fluence may be controlled by coupling the controller 212 to the pumping device of each energy generator 202A-D. The controller 212 can be programmed to generated pulses of energy 214A-D from the four energy generators 202A-D, with each pulse having different fluence and duration, and each pulse being released at specific times in relation to each other.

[0039] The pulses 214A-D travel into the collector 204, which aligns the pulses 214A-D along a single output optical axis 216 for relaying to a substrate positioned on the work surface. The collector 204 has a plurality of input optical axes for receiving the energy pulses 214A-D from the energy source 202. The collector 204 generally has various optical devices, such as lenses, mirrors, prisms, and filters that bring the incident energy pulses 214A-D to the optical axis 216.

[0040] Energy aligned on the optical axis 216 enters the shaper 206. The shaper has optical devices such as lenses, mirrors, prisms, and filters that convert a native energy pulse from the energy generators 202A-D into a shaped pulse having a desired spatial power distribution and temporal shape. The shaper 206 may combine two or more separate pulses to form one combined pulse having a composite shape. The shaper 206 thus produces an energy field having a shape that matches a treatment area of the substrate and a uniform distribution of power to process the treatment area uniformly.

[0041] The shaped energy 218 processes a substrate positioned on the work surface 208. The work surface 208 is typically movable, as indicated by arrow 210, to allow positioning various treatment areas of the substrate opposite the energy emerging from the shaper 206.

[0042] The apparatus 200 may include an optional acoustic sensor 220 positioned proximate the work surface 208 to receive acoustic signals from a

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