electrode positioned close to the wafer surface creates an electric field to control the number of electrons which stay on the wafer. During inspection, the wafer floats at a potential controlled by a power supply.

Flooding and swathing are typically commonly done sequentially but may be done simultaneously. Flooding and swathing generally operate on different areas of the sample. In swathing, the sample is imaged by rastering the primary beam in one direction (e.g., the X-direction) while the sample translates in a perpendicular direction (e.g., the Y-direction). By way of example, during a wafer inspection, a stage moves the sample such that an area of the sample is flooded before it is inspected. Flooding is typically either on or off for the entire duration of a swath. Because flooding covers a significantly larger area than a swath, flooding may be turned off, e.g., at least every other swath. To prolong the life of the flood gun, the flood gun beam may be blanked, e.g., by applying a suitable voltage to the extractor, when not needed.

It is within this context that aspects of the present disclosure arise.

BRIEF DESCRIPTION OF THE DRAWINGS

Objects and advantages of aspects of the present disclosure will become apparent upon reading the following detailed description and upon reference to the accompanying drawings in which:

FIG. 1 is a schematic diagram of an electron beam imaging apparatus according to an aspect of the present disclosure.

FIG. 2 is a schematic diagram of a flood gun portion of an electron beam imaging apparatus according to an aspect of the present disclosure.

FIG. 3 is a schematic diagram of a flood gun portion of an electron beam imaging apparatus according to an aspect of the present disclosure.

FIG. 4 is a schematic diagram of a flood gun portion of an electron beam imaging apparatus according to an aspect of the present disclosure.

FIG. 5 is a schematic diagram of an electron beam imaging apparatus according to an aspect of the present disclosure.

the column **102** and is configured to provide a flood beam coaxially with the primary beam **106** as shown in FIG. 1.

The primary electron gun **104**, condensing lenses **108**, scanning coils **110**, objective lens **112**, stage **115**, detector **116**, and flood gun **200** may be operably coupled to a controller **120**, which may include power supplies configured to provide voltages and/or currents to these elements in response to hardware or software instructions. The controller **120** may include a special purpose computer or a general purpose computer configured to operate as a special purpose computer upon execution of code instructions **122**, which may be stored in a computer memory or other non-transitory computer readable medium.

According to aspects of the present disclosure, the apparatus **100** may be used to implement charge control during sample inspection according to an inventive method. According to the method a first area of the sample **114** within a first region of the sample may be imaged with the primary beam **106** of electrons from the primary column **102**. The first area of the sample may then be charged with a beam of charged particles from the flood gun **200**. A second area of the sample within the first area may then be imaged with the primary beam of electrons from the primary column **102**. The configuration of the apparatus **100** allows a time between ending imaging of the first area and beginning imaging of the second area to be less than one second.

Method

Aspects of the present disclosure include implementations in which flooding and swathing occur simultaneously, but on different areas of the sample. In swathing, the sample is imaged by rastering the primary beam **106** in one direction (e.g., the X-direction) while the sample **114** translates in a perpendicular direction (e.g., the Y-direction) and a swath image is taken across a width of the sample. By way of example, during a wafer inspection, the stage **115** may move the sample **114** while the flood gun **200** provides a flood beam such that an area of the sample being swathed is flooded before it is inspected with the primary beam. To prolong the life of the flood gun, the flood gun beam may be blanked, e.g., by applying a suitable voltage to the extractor, when not needed.

Alternative Implementations

Image acquisition may take longer than flooding, e.g., from about 0.2 seconds to about 1 second. During operation in the imaging mode, the primary beam from the imaging/inspection device strikes an imaging area within the flood area and causes the emission of secondary electrons or the release of backscattered electrons from the image area. The secondary electrons (and/or the backscattered electrons) are then detected by the detector **116** for further process and analysis. The primary beam may move to another image area within the flood area for image acquisition. Once image acquisition in the flood area is done, the stage moves to next location of interest. The apparatus then switches to the flood mode and the process may start over again.

FIGs. 3 and 4 are schematic diagrams of a flood gun using a micro-channel plate as electron source according to an aspect of the present disclosure. For simplicity, identical reference numbers are used to identify components in FIGs. 3 and 4 which are identical to the components in FIG. 2. The description of similar or identical elements is not repeated.

The electron source of flood gun **300** includes an initiating radiation source **312**, a micro-channel plate (MCP) **314** and an extractor grid (not shown). The initiating radiation source is configured to initiate generation of charged particles by the MCP plate by supplying radiation to the MCP **314** that initiates emission of electrons, e.g., by photoemission. The initiating radiation source **312** may be a light source of appropriate wavelength for the photo cathode of the MCP. By way of example and not by way of limitation, the initiation radiation source **312** includes an ultraviolet light emitting diode (LED) or a laser. The secondary electrons from the interaction between the radiation and the MCP are then extracted by the extractor grid. A condenser electrode (not shown) may be included to focus the charged particles extracted by the extractor grid and thereby forming a flood beam of charged particles. The MCP **314** can be turned on and off rapidly switching the initiating radiation source on and off. Alternatively, this may be accomplished by high speed voltage supplies **315a-c** while the initiating radiation source **312** is turned on. It is noted that the flood current is adjustable with the MCP gain. In some embodiments, there are a stack of MCPs for additional gains. FIG. 4 is similar to FIG. 3, except for the location of the beam-defining aperture (BDA) for the primary beam. In FIG. 3, the BDA is provided between the MCP **314** and the sample. In FIG. 4, the MCP **314** is provided between the BDA and the sample. In FIG. 4 the high voltage applied to the flood gun to accelerate the flood electrons may be shut down when the

flood gun is not in operation. Doing so avoids the need for a shield mesh to shield the primary beam.

Aspects of the present disclosure are not limited to implementations in which the flood beam source is coaxial with the primary beam source, as in FIG. 1. Many other possible configurations are within the scope of aspects of the present disclosure. For example, FIG. 5 is a schematic diagram of an apparatus according to an aspect of the present disclosure. The apparatus of FIG. 5 is similar to the apparatus of FIG. 1, except for the location of the flood gun. The flood gun **200** of FIG. 1 is provided along the axis of the primary beam **106** while the flood gun **600** is provided off the axis of the primary beam. The flood gun **600** may be a conventional flood gun **600a** as shown in FIG. 6, a flood gun **600b** having a MCP source as shown in FIG. 7 or a flood gun **600c** having nanotube array emitters as shown in FIG. 8. As in the apparatus **100** of FIG. 1, the primary electron gun **104**, condensing lenses **108**, scanning coils **110**, objective lens **112**, stage **115**, detector **116**, flood gun **600**, and deflector **650** may be operably coupled to a controller **120**. The controller may include a special purpose computer or a general purpose computer configured to operate as a special purpose computer upon execution of code instructions **122**, which may be stored in a computer memory or other non-transitory computer readable medium.

Aspects of the present disclosure include implementations in which the flood beam source is not coaxial with the primary beam but the flood beam and primary beam are at least partly coaxial. For example, FIG. 6 illustrates an implementation in which the beam from an off-axis conventional flood gun **600a** may be deflected to be coaxial with the primary beam proximate the sample. Such an implementation may be included in an apparatus **500** of FIG. 5. In this implementation, the primary beam is shielded from the flood high voltage by a grounding device, including grounding structures **680** and a ground mesh **681**. Additionally, a deflector **650** is included in apparatus **500** so as to steer the flood beam **612** toward the axis of the primary beam **106**. In one embodiment, the deflector **650** may be conventional electrostatic deflectors. In another embodiment, the deflector **650** may be a Wien filter. Specifically, a Wien filter provides a E×B field (e.g., one in which electric and magnetic fields are perpendicular to each other and to the primary beam's path to exert oppositely directed forces on the primary beam). The magnitude of the magnetic force depends on strength of the magnetic field and the speed of the particles in the primary beam but the magnitude of the electric force depends only on the strength of the electric field. The Wien

filter is normally calibrated to allow primary image beam **106** to pass straight through, while secondary electrons, which travel in the opposite direction will be deflected by the Wein filter to the detector **116**. To fast switch the flood beam **612** on axis, the electric field of the Wien filter can be reversed by switching the polarity of the voltages applied to the field plates. This will cause the flood beam **612** to be steered onto the optical axis. Secondary electrons resulting from interaction between the flood beam **612** and the sample will not be deflected toward the detector.

FIG. 7 illustrates an alternative flood gun **600b** that may be included in an apparatus **500** of FIG. 5. The electron source of flood gun **600b** includes an initiating radiation source **602**, a micro-channel plate (MCP) **604** and an extractor grid (not shown). The initiating radiation source is configured to initiate generation of charged particles by the MCP plate. The initiating radiation source **602** may be a light source of appropriate wavelength for the photo cathode of the MCP. By way of example and not by way of limitation, the initiation radiation source **602** includes an ultraviolet light emitting diode (LED) or a laser. The secondary electrons from the interaction between the radiation and the MCP are then extracted by the extractor grid. An on-axis mesh lens **606** may be included to focus the charged particles extracted by the extractor grid and thereby forming a flood beam of charged particles. The MCP **604** is configured to be turned on and off rapidly by, e.g., high speed voltage supplies. A blanking electrode/mesh **608** may be provided between the MCP **604** and the lens **606** for disabling the flood gun.

FIG. 8 illustrates another alternative flood gun **600c** that may be included in an apparatus **500** of FIG. 5. The electron source of flood gun **600c** includes a nanotube array emitter **605**, and an extractor grid **608** may be provided between the emitter **605** and an on-axis mesh lens **606**. The nanotube array emitter generates electrons by field emission when a voltage is applied to an array of nanotubes. Due to the small diameter of the nanotubes (e.g., order of a few nanometers or less), a high electric field exists at the tips of the nanotubes when the voltage is applied. The electrons emitted from the nanotubes by field emission are extracted by the extractor grid. A voltage applied to the mesh lens **606** may be configured to focus the charged particles extracted by the extractor grid **608** and thereby form a flood beam. The extractor grid **608** may operate as a blanking electrode/mesh **608** to disable current from the flood gun **600c**. Furthermore, the high voltage applied to the flood gun **600c** to accelerate the flood electrons may be shut down when the flood gun is not in operation. Doing so avoids

the need to shield the primary beam. The power supply that provides voltage between the extractor grid **608** and the emitter **605** may be high switching speed voltage supplies configured to be turned on and off rapidly, e.g., at greater than 1 Hz, more preferably greater than 10 Hz, still more preferably at greater than 100 Hz and even more preferably, greater than 1000 Hz.

According to an aspect of the present disclosure, an electron beam imaging system having a flood gun may operate in an in-situ closed-loop flood mode to terminate flooding. Specifically, as illustrated with respect to FIG. 9, a system may have a flood gun **900**, flood gun controller **905**, a flood detector energy filter **910**, a flood detector **915**, and a trigger circuit **920** connected to the flood detector **915** and the flood gun controller **905**.

The flood gun **900** may be any type of flood gun described herein or a conventional flood gun. The flood gun **900** may be configured so that part of the flood beam **901** is coaxial with a primary beam **106** for a charged particle beam imaging system (e.g., a scanning electron microscope) over a portion of the primary beam path proximate a sample **114**. A deflector (not shown), e.g., a Wien filter or electrostatic deflector plates, may steer the flood beam **901** into coaxial alignment with the primary beam **106** proximate the sample **114**. The flood detector is configured to detect secondary electrons **903** and backscattered electrons from the sample **114** due to the flood beam **901**. The imaging system may include a separate detector (not shown) to detect secondary electrons emitted from the sample during imaging.

The flood detector energy filter **910** may be a simple grid placed between the sample **114** and the flood detector **915**. A voltage from a power supply **912** is applied to the grid, which repels electrons having a total energy less than some energy that depends on the grid voltage. The grid may have a small aperture that allows the primary beam **106** a clear path to pass through the energy filter **910** unimpeded during imaging operation.

The illustrated system may operate as follows. The primary beam **106** is switched off prior to flooding. The flood detector energy filter **910** is set to a voltage corresponding to a desired surface charge voltage added to the bias voltage applied to the sample wafer bias WB (if any). For example if the desired surface charge voltage is +20V, a voltage of WB+20V would be applied to the energy filter **910**. The controller **905** may trigger the flood gun **900** to begin an in-situ flood pulse. As the flood pulse begins the flood beam **901** charges the

sample and the sample voltage begins to change as a result of the charging. The sample voltage could rise or fall but for the purposes of example, consider a case where the sample voltage rises. As the sample voltage rises secondary electrons and backscattered electrons leave the sample **114** with progressively lower total energy.

When the surface charge voltage reaches the desired value (e.g., +20V in this example) the secondary electron signal at the flood detector **915** begins to get cutoff by the energy filter **910**. The energy filter **910** does not need to be particularly accurate so long as it is sufficiently precise. The trigger circuit **920** detects the drop in signal from the flood detector and triggers the flood gun controller **905** to end to the flood pulse.

If the flood beam current is sufficiently large, the secondary electron and backscattered electron yield from the sample during flooding may be larger than 100 microamps (μA). Even if the flood detector collects only a portion of the secondary and backscattered electrons this should still be sufficient for the flood detector signal to have an adequate signal to noise ratio (SNR) with little gain.

Operation in an in-situ closed-loop mode allows for very fast flooding. If flooding can be done sufficiently fast, e.g., much less than 1 μs, it may be possible to start and finish flooding the sample as the primary beam (or beam steering voltage/current, if the beam is turned off) flies back across the imaged portion of the sample at the end of a line of an imaging scan with the primary beam in the x-direction before the primary beam begins the next line scan of the image.

According to an aspect of the present disclosure, an electron beam imaging system having a flood gun may operate in an alternative in-situ closed-loop to measure the voltage applied to the energy filter **910** while flooding. By reading back the value of the energy filter voltage as the sample is flooded, one can track the surface potential value and rate of change of surface voltage. This can be used to identify large area defects, for instance, a contact array with excessive leakage. FIG. 10A depicts an apparatus that is similar to the apparatus of FIG. 9. However, instead of a trigger circuit connected to flood detector **915** and the flood gun controller **905**, a gated integrator **930** is coupled between the flood detector and the energy filter power supply **912**. The gated integrator **930** integrates a signal input (e.g., a current)

from the flood detector after a defined waiting time (trigger delay) over a specified period of time (gate width) and then average over multiple integration results (samples).

In operation, the energy filter **910** is biased to some voltage e.g., -5V, with respect to the surface potential of the sample. This causes the energy filter to "cut off", or reject, all secondary electrons (SE) with less than 5eV of initial energy. In this example only electrons with greater than 5 eV energy would make it to the detector **915**. Consequently, the detector current to the gated integrator **930** is a value corresponding to 5eV and above electrons. The gated integrator includes a summing junction that subtracts a DC current set to the expected value of the detector current. The output of the summing junction feeds the integrator. When the detector current equals the reference current no voltage is integrated. When the detector current is different from the reference current, voltage is added or subtracted. The output of the integrator is added to the energy filter voltage. If, e.g., the flood beam **901** charges the sample **114** positively, the detector current will begin to decrease causing a mismatch with the reference current and the integrator **930** will produce a digital output that adjusts the energy filter voltage from power supply **912** to follow the surface potential of the sample **114**. This signal may be read by a system controller (not shown) to track the surface potential.

By way of example, and not by way of limitation, FIG. 10B depicts a possible configuration of a gated integrator **930'** that may be used in the apparatus of FIG. 10A. The integrator **932'** includes first, second, third, and fourth cascaded amplifiers **932A**, **932B**, **932C**, **932D**, and a capacitor bank **934**. A current signal from the detector **915** can be coupled to an input of the first amplifier **932A**. A first digital to analog (D/A) converter **935** coupled between an output of the first amplifier **932A** and an input of the second amplifier **932B** is set to null the expected average detector current. A gate switch **936** between the output of the second amplifier **932B** and an input of the third amplifier may be used to gate the integrator when the flood beam **901** is blanked, e.g., during flyback of the sample **114**. The capacitor bank **934** includes multiple different switched capacitors that are coupled in parallel between an input and an output of the third amplifier **932C**. Each capacitor in the capacitor bank **934** has a corresponding switch. By selectively opening or closing the switches a particular combination of capacitors can be used to set the integration time constant for different scan rates. Selectively opening and closing the switches may also be used to reset the integrator.