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Potter

(10) **Patent No.: US 7,217,582 B2**
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(54) **METHOD FOR NON-DAMAGING CHARGE INJECTION AND A SYSTEM THEREOF**

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(51) **Int. Cl.**
H01L 21/00 (2006.01)

(52) **U.S. Cl.** **438/19**; 438/48; 438/778; 438/795; 257/E21.192

(58) **Field of Classification Search** 438/19, 438/48–53, 778, 795, E21.192; 427/255.37
See application file for complete search history.

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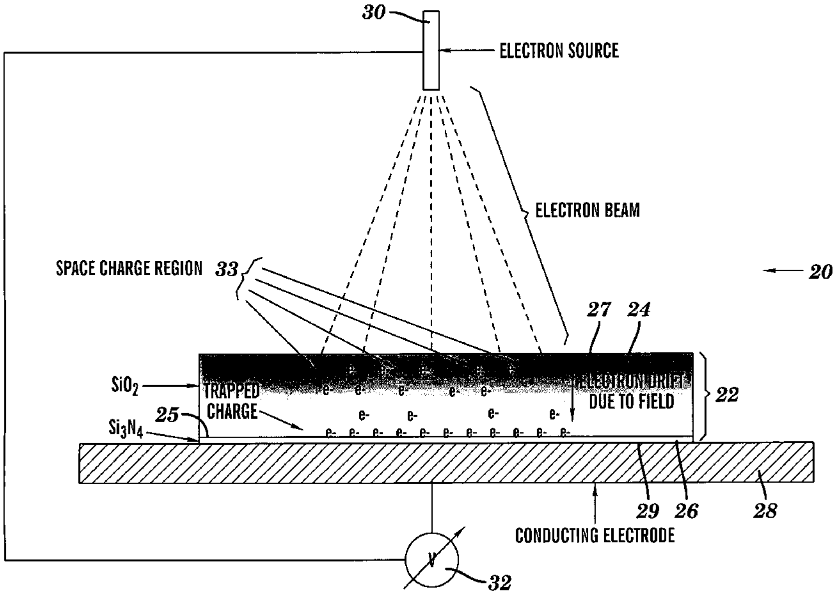
(57) **ABSTRACT**

A method and system for injecting charge includes providing a first material on a second material and injecting charge into the first material to trap charge at an interface between the first and second materials. The thickness of the first material is greater than a penetration depth of the injected charge in the first material.

9 Claims, 3 Drawing Sheets



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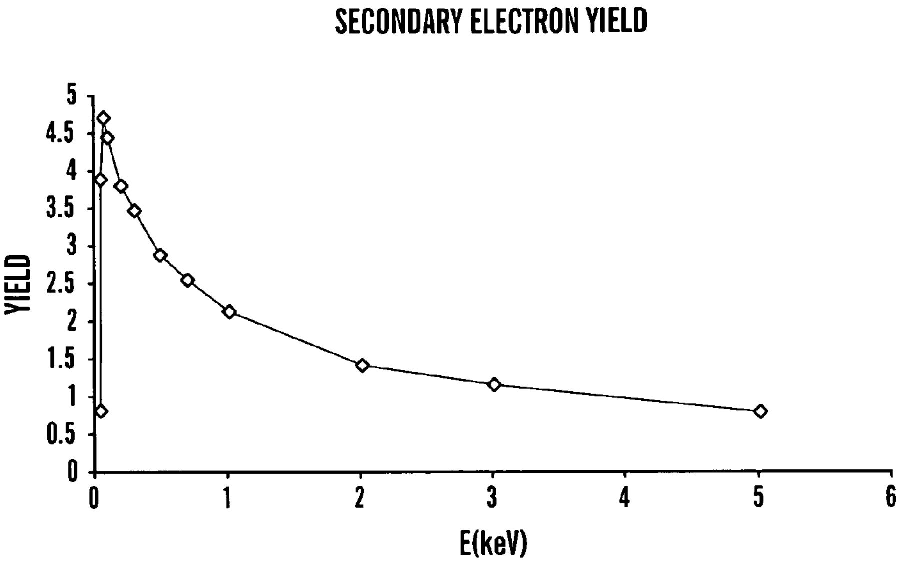
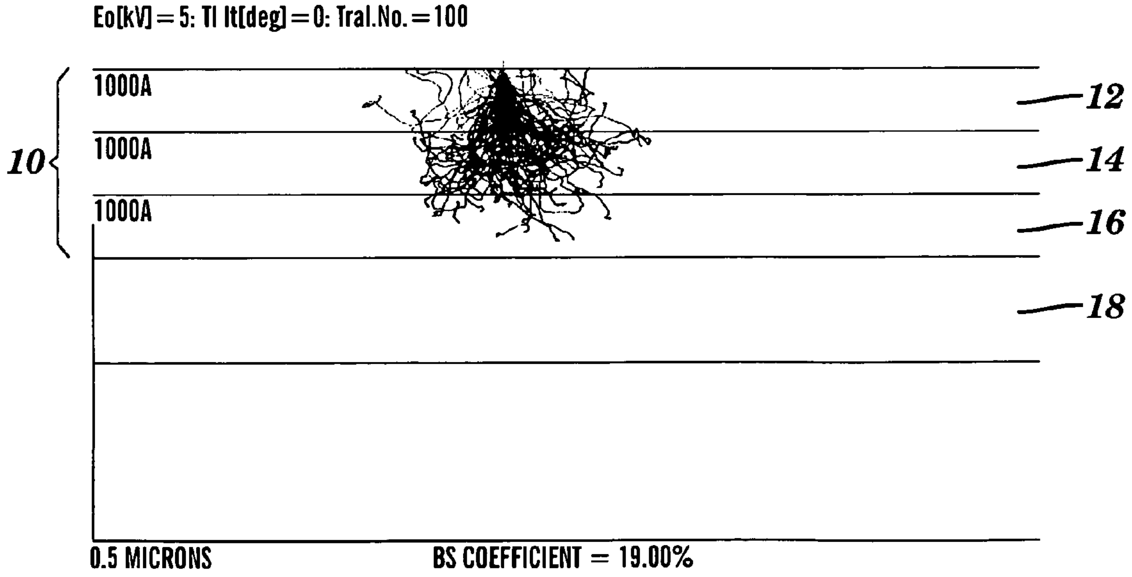


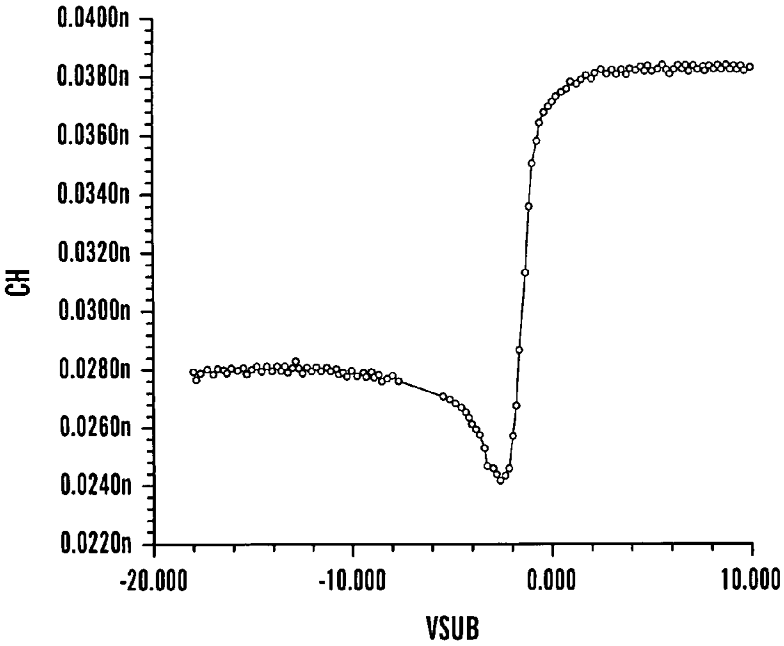
SECONDARY ELECTRON YIELD AS A FUNCTION OF ACCELERATING POTENTIAL

FIG. 1



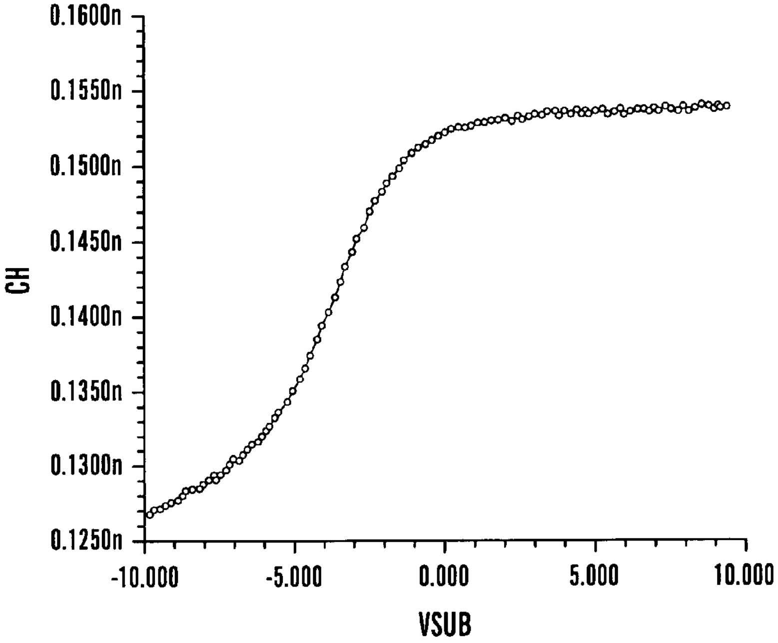
MONTE-CARLO SIMULATION OF 5KeV BALLISTIC ELECTRON INJECTION INTO A COMPOSITE INSULATOR

FIG. 2



ICS 16:38:45 Initial
04/14/2003

FIG. 3A



ICS 08:11:46 AFTER ELECTRON INJECTION
04/15/2003

FIG. 3B

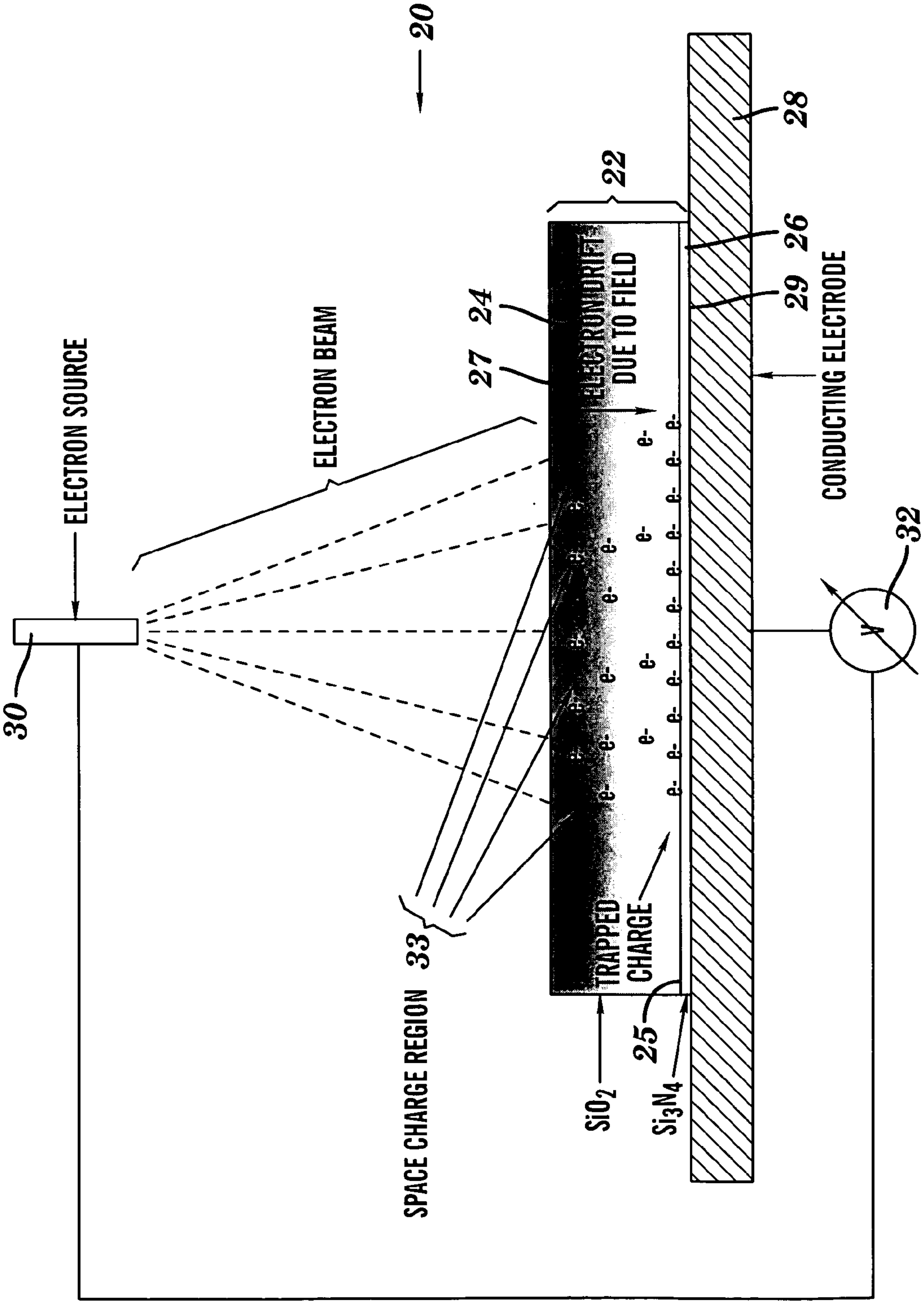

20
ELECTRON SOURCE
30
ELECTRON BEAM
27
24
22
28
26
29
ELECTRON DRIFT DUE TO FIELD
CONDUCTING ELECTRODE
e-
32
V
TRAPPED CHARGE
SPACE CHARGE REGION 33
SiO_2
Si_3N_4
25

FIG. 4

METHOD FOR NON-DAMAGING CHARGE INJECTION AND A SYSTEM THEREOF

The present invention claims the benefit of U.S. Provisional Patent Application Ser. No. 60/498,827, filed Aug. 29, 2003, which is hereby incorporated by reference in its entirety.

The subject invention was made with government support (Infotonics Technology Center (DOE)) Award No. DEFG02-02ER63410.A100. The U.S. Government may have certain rights.

FIELD OF THE INVENTION

The present invention generally relates to charge injection and, more particularly, relates to a method for non-damaging charge injection and a system thereof.

BACKGROUND

Recently, a new class of Micro-Electrical-Mechanical Systems (MEMS) devices have been disclosed that utilize embedded electronic charge as a means for actuation or self-generating sensors, such as those disclosed in U.S. Pat. Nos. 6,597,560; 6,638,627; 6,688,179; 6,717,488; 6,750,590; and 6,773,488 and in US Patent Application Publication Nos.: 2002/0131228; 2002/0182091; 2003/0079543; 2003/0201784; and 2004/0023236 by way of example. Typically, charge is injected into the interface of dissimilar insulating materials by high electric field injection. Electrons "e-" are caused to tunnel into the conduction band of a material, such as silicon dioxide, from a silicon substrate via a high-applied electric field. The electrons "e-" become trapped at electronic trap sites at a composite insulator interface, such as an interface between silicon dioxide and silicon nitride. The charge remains trapped for an extremely long period of time and is therefore useful as MEMS enabling technology.

Embedded electronic charge is also useful for other macroscopic applications, such as, but not limited to, harvesting energy from the environment. These macroscopic structures include windmills that can convert the energy of wind into electrical power. However, for macroscopic structures it is impractical to embed electronic charge by tunneling into the conduction band of one member of insulating composite large structures. Typically, a suitable injecting interface, such as silicon to silicon dioxide, is not available.

One technique that has been investigated is to expose the structure to a beam of energetic particles such as an electron beam. With this technique, electrons "e-" impinge upon a surface of a composite insulating structure with sufficient energy to enter the system. These electrons "e-" are then trapped at trap sites at a dissimilar insulator interface.

Unfortunately, there is significant difficulty with this ballistic electron injection process. It is important that the energy of the arriving electrons "e-" be either below or above the range of energies where secondary electron yield is greater than unity. If the energy is within the range of greater than unity, a net positive charge can significantly affect the result. For example, positive charge within the outermost insulator layer, but close to the embedded electron charge will tend to empty the traps via internal high field, thus neutralizing the effective trapped charge. Furthermore, the simple presence of opposite sign charge in the vicinity of the trapped charge will tend to neutralize the effectiveness of the trapped charge.

Referring to FIG. **1**, a graph of a secondary electron yield of silicon dioxide as a function of electron energy is shown. The data in the graph shows that the secondary electron yield is greater than unity from about 30 eV to approximately 3,800 eV. It is obvious any accelerating potential less than 30 eV does not have sufficient energy to substantially enter the system. Therefore, one must use energies greater than about 3,800 eV.

It is also desirable to create a system where the charge is as close to the surface as possible. As a result, the thickness of the outermost layer must be thin. However, as described above, the accelerating potential must be kept above the critical value of about 3,800 eV. With a thin outermost layer and the accelerating potential above about 3,800 eV, the penetration of the electrons "e-" may be too great.

Referring to FIG. **2**, a graph of a Monte Carlo simulation of electron penetration into a composite **10** of a layer of silicon dioxide **12** on a layer of silicon nitride **14** on a layer of silicon dioxide **16** that is on a substrate **18** of silicon is illustrated. The layer of silicon dioxide **12**, the layer of silicon nitride **14**, and the layer of silicon dioxide **16** each have a thickness of about 100 nm. The thickness of the outermost layer of silicon dioxide **12** is chosen so that the average penetration depth of the arriving electrons "e-" is at the interface between the outermost layer of silicon dioxide **12** and the layer of silicon nitride **14**. Unfortunately, this ballistic charge injection technique has not been shown to be effective.

Referring to FIGS. **3**A and **3**B, the capacitance-voltage (C-V) characteristics before and after the ballistic injection into the composite **10** are shown. The tests were performed on the composite **10** of a layer of silicon dioxide **12** on a layer of silicon nitride **14** on a layer of silicon dioxide **16** with the substrate **18** of n-type silicon with a liquid InGa top electrode. The ballistic injection parameters were 3 KeV, 100 sec., and 3,000 $\mu C/cm^2$ dose.

As the graphs in FIGS. **3**A and **3**B show, there is severe degradation in the post-injection characteristics of the composite **10**. This is presumed to be due to morphological changes creating defects. These defects apparently have a wide energy distribution and significant dipole moment. Investigations have determined poor retention time of charge for these test structures. Furthermore, the maximum-trapped charge density for these investigations is much less than that achieved using high field tunneling. Since the accelerating potential was in the range of secondary electron yield greater than unity, a slight negative shift is observed indicating the presence of positive charge.

SUMMARY OF THE INVENTION

A method for injecting charge in accordance with embodiments of the present invention includes providing a first material on a second material and injecting charge into the first material to trap charge at an interface between the first and second materials. The thickness of the first material is greater than a penetration depth of the injected charge in the first material.

A system for injecting charge in accordance with embodiments of the present invention includes a first material on a second material with an interface between the first and second materials and a charge source positioned to inject charge into the first material to trap charge at an interface between the first and second materials. The thickness of the first material is greater than a penetration depth of the injected charge in the first material.

The present invention provides a system and method for injecting charge to fill the electronic traps at an interface between materials without causing deleterious effects on charge storing characteristics of the materials. The resulting structure with the trapped charge at an interface is particular useful for MEMS enabling technology, but can be used to inject charge in other types of devices.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. **1** is a graph of secondary electron yield as a function of accelerating potential;

FIG. **2** is a graph of a Monte Carlo simulation of 5 KeV ballistic electron injection into a composite insulator;

FIG. **3**A is a graph of C-V characteristics in a composite insulator before electron injection;

FIG. **3**B is a graph of C-V characteristics in a composite insulator after electron injection; and

FIG. **4** is a system for non-damaging electron injection in accordance with embodiments of the present invention.

DETAILED DESCRIPTION

A system **20** for non-damaging electron injection in accordance with embodiments of the present invention is illustrated in FIG. **4**. The system **20** includes a structure **22** comprising a layer of silicon dioxide (SiO_2) **24** on a layer of silicon nitride (Si_3N_4) **26**, a conducting electrode **28**, a ballistic electron source **30**, and a power source **32**, although the system **20** can comprise other types and numbers of components arranged in other manners. The present invention provides a number of advantages including providing a system **20** and method for injecting charge to fill the electronic traps at an interface **25** between layers **24** and **26** that does not cause deleterious effects on charge storing characteristics of the interface **25** between the layers **24** and **26** of the structure **22**.

Referring more specifically to FIG. **4**, the structure **22** comprises the layer of silicon dioxide (SiO_2) **24** on the layer of silicon nitride (Si_3N_4) **26**, although other types and numbers of dissimilar insulating layers which are arranged in other manners can be used. An interface **25** is formed between the layer of silicon dioxide **24** and the layer of silicon nitride **26** at which the trapped charge is stored.

The thickness of the layer of silicon dioxide **24** from an outer surface **27** of the layer **24** to the interface **25** is about 500 micron, although the layer of silicon dioxide **24** could have other thicknesses. The thickness of the layer of silicon dioxide **24** is greater than a penetration depth of electrons "e-" injected into the layer of silicon dioxide **24** from the ballistic electron source **30**. The layer of silicon nitride **26** has a thickness of about 100 nm in this example, although the layer of silicon nitride **26** can have other thicknesses.

The conducting electrode **28** is placed on another surface **29** of the layer of silicon nitride **26**, although other manners for coupling the layer of silicon nitride **26** to the conducting electrode **28** can be used. A variety of different types of conducting materials can be used for the conducting electrode **28**.

The ballistic electron source **30** is an electron flood gun for injecting electrons "e-", although other types of charge sources can be used and other types of charge can be injected. The ballistic electron source **30** is positioned and used to inject electrons "e-" through surface **27** into the layer of silicon dioxide **24**. The energy of the electrons "e-" from the ballistic electron source **30** is above the energy where secondary electron yield is unity. In these embodiments, the level of energy is above 3,800 eV and may be on the order of 5,000 eV to 500,000 eV, although other levels of energy can be used. The injected electrons "e-" quickly will thermalize to the conduction band minimum of the layer of silicon dioxide **24**. Since the number of injected electrons "e-" is substantially greater than the secondary electrons, a local negative space charge **33** is established. This will likewise establish an electric field between the space charge and the conducting electrode **28** that is substantially in contact with the surface **29** of the layer of silicon nitride **26**.

The power source **32** applies a potential difference between the conducting electrode **28** and the electron source **30** which establishes an accelerating potential for the electrons "e-" or other charge being injected, although the power supply **32** can be coupled to provide power in other manners. An application of positive bias to the conducting electrode **28** by the power source **32** may enhance the electric field across the layer of silicon dioxide **24** and the layer of silicon nitride **26**.

A method for non-damaging electron injection in accordance with embodiments of the present invention will now be described with reference to FIG. **4**. The layer of silicon nitride **26** is deposited on to the layer of silicon dioxide **24**, although the layers **24** and **26** can be formed in other manners. The layer of silicon dioxide **24** has a thickness which is greater than a penetration depth of electrons "e-" injected into the layer of silicon dioxide **24** from the ballistic electron source **30**. The thickness for the layer of silicon dioxide **24** is determined by a Monte Carlo simulation taking into account the acceleration potential supplied by the power source **32** between the conducting electrode **28** and the electron source **30** and the materials properties of the layer being injected into, in this example the layer of silicon dioxide **24**, although other techniques for determining the thickness of the layer so that it is greater than the penetration depth of the charge being injected can be used. The layer of silicon dioxide **24** on the layer of silicon nitride form the structure **22**, although again the structure **22** can have other numbers and types of layers.

Next, the conducting electrode **28** is placed on the surface **29** of the layer of silicon nitride **26**, although other manners for coupling the layer of silicon nitride **26** to the conducting electrode **28** can be used. The power source **32** is coupled to the conducting electrode **28** and to the ballistic electron source **30** to apply a potential difference between the conducting electrode **28** and the ballistic electron source **30** which establishes an accelerating potential for the charge, in these embodiments the electrons "e-". The applied accelerating potential is at a value where secondary electron yield is less than unity. The power source **32** may also apply a positive bias to the conducting electrode **28**, although other biasing arrangements can be used, such as having the conducting electrode **28** coupled to ground.

The ballistic electron source **30** emits electrons "e-" in an electron beam towards the surface **27** of the layer of silicon dioxide **24**, although other types of charge could be used. The electrons "e-" penetrate through the surface **27** and into the layer of silicon dioxide **24**, but not to the interface **25** because the thickness of the layer of silicon dioxide **24** is greater than the substantial maximum penetration depth of the electrons "e-" being injected.

Electrons "e-" injected in the layer of silicon dioxide **24** from the ballistic electron source **30** migrate toward the interface **25** between the layer of silicon dioxide **24** and the layer of silicon nitride **26** because of an electric field from a space charge region **33** in the layer of silicon dioxide **24** to the conducting electrode **28**. The layer of silicon dioxide

24 is a wide band gap material with a band gap of approximately 9 eV making it an excellent insulator. However, the layer of silicon dioxide **24** is basically a contact limited insulator. An electron in the conduction band of the layer of silicon dioxide **24** is actually reasonably mobile, on the order of 1 to 10 cm^2 per volt-second. As a result, the injected electrons "e-" quickly fill the traps at the interface **25** and remain there. Any morphological damage layer of silicon dioxide **24** is well away from the interface **25** between the layer of silicon dioxide **24** and the layer of silicon nitride **26** and will not degrade the characteristics of the trapped electrons, such as retention time. The trapped charge, in these embodiments electrons "e-", at the interface **25** is monopole charge.

If desired, a layer of photo resist or other protective material can be coated over the layer of silicon nitride **26** and a portion of the layer of silicon dioxide **24** may be etched away where the injection of the electrons "e-" caused damage. By way of example only, hydrofluoric acid, can be used to remove the damaged portion of the layer of the silicon dioxide **24**, if desired. The layer of photo resist is then removed and the structure **22** is ready for use in applications.

Accordingly, as described above, the present invention provides a system **20** and method for injecting charge to fill the electronic traps at an interface **25** between layers **24** and **26** that does not cause deleterious effects on charge storing characteristics of the interface **25** between the layers **24** and **26** of the structure **22**.

Having thus described the basic concept of the invention, it will be rather apparent to those skilled in the art that the foregoing detailed disclosure is intended to be presented by way of example only, and is not limiting. Various alterations, improvements, and modifications will occur and are intended to those skilled in the art, though not expressly stated herein. These alterations, improvements, and modifications are intended to be suggested hereby, and are within the spirit and scope of the invention. Additionally, the recited order of processing elements or sequences, or the use of numbers, letters, or other designations therefor, is not intended to limit the claimed processes to any order except as may be specified in the claims. Accordingly, the invention is limited only by the following claims and equivalents thereto.

What is claimed is:

1. A method for injecting charge, the method comprising:

providing a first material on a second material; and

injecting charge into the first material to trap charge at an interface between the first and second materials, wherein a thickness of the first material is greater than a penetration depth of the injected charge in the first material, wherein the first and the second materials are dissimilar insulators.

2. The method as set forth in claim **1** further comprising:

providing a conductor on the second material;

providing a source for the injected charge which is positioned to direct the injected charge towards at least a portion of the first material; and

applying an accelerating potential across the conductor and the source for the injected charge.

3. The method as set forth in claim **2** wherein the applied accelerating potential is at a value where secondary electron yield is less than unity.

4. The method as set forth in claim **2** wherein the applied accelerating potential is above 3800 eV.

5. The method as set forth in claim **1** further comprising determining the penetration depth of injected charge in the first material, wherein the providing further comprises depositing the first material on the second material to the thickness which is greater than the determined penetration depth.

6. The method as set forth in claim **1** further comprising removing a portion of the first material where the injected charge has penetrated.

7. The method as set forth in claim **6** further comprising coating at least a portion of the second material with a protective layer during the removal of the portion of the first material.

8. The method as set forth in claim **1** wherein the first material comprises SiO_2 and the second material comprises Si_3N_4.

9. The method as set forth in claim **1** wherein the charge trapped at the interface is monopole charge.

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