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Photon-induced conduction modulation in SiO_2 thin films embedded with Ge nanocrystals

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The authors report the photon-induced conduction modulation in SiO_2 thin films embedded with germanium nanocrystals (nc-Ge). The conduction of the oxide could be switched to a higher- or lower-conductance state by a ultraviolet (UV) illumination. The conduction modulation is caused by charging and discharging in the nc-Ge due to the UV illumination. If the charging process is dominant, the oxide conductance is reduced; however, if the discharging process is dominant, the oxide conductance is increased. As the conduction can be modulated by UV illumination, it could have potential applications in silicon-based optical memory devices. © *2007 American Institute of Physics*. [DOI: 10.1063/1.2711198]

Si and Ge nanocrystals embedded in SiO_2 matrix have been demonstrated as the potential candidates for the fabrication of Si-based optoelectronic devices[1,2] and nonvolatile memory devices[3,4] that are compatible with the main stream complementary metal-oxide-semiconductor process. One of the promising techniques being used to synthesize such structures is the implantation of Si or Ge ions into SiO_2 films followed by high temperature annealing. The memory effect of semiconductor nanocrystals embedded in SiO_2 thin films synthesized with low energy ion implantation followed by subsequent annealing has been demonstrated by several research groups.[3,5–9] In these nanocrystals-based memory devices, the conventional polysilicon floating gate is replaced by isolated nanocrystals embedded in the gate oxide which can increase the retention time, scalability, and reliability. In this letter, we report a conduction modulation effect of SiO_2 films embedded with Ge nanocrystals (nc-Ge) caused by ultraviolet (UV) illumination. Unlike the conventional metal-oxide-semiconductor (MOS) structures with nanocrystals embedded in the gate oxide, we fabricated a MOS-like device structure of which the metal gate was replaced by indium tin oxide (ITO). In this study, the ITO film plays the role as a semitransparent electrode with which the light can penetrate the gate electrode.

A 30 nm SiO_2 thin film was thermally grown in dry oxygen at 950 °C on *p*-type Si(100) wafer. Ge ions with a dose of 2×10^{15} cm^{-2} were then implanted into the SiO_2 thin film at the energy of 6 keV. Thermal annealing was carried out in N_2 ambient at 800 °C for 60 min. Finally, a 130 nm ITO thin film was deposited on the Ge^+-implanted SiO_2 thin film to form a semitransparent gate electrode with a diameter of 1.2 mm. Details of the ITO deposition and characterization can be found in previous studies.[10,11] The device structure is presented in Fig. 1(a). As revealed by the simulation of stopping and range of ion in matter (SRIM) shown in Fig. 1(b), the implanted Ge distributes from the oxide surface to a depth of ~20 nm. The formation of nc-Ge was con-

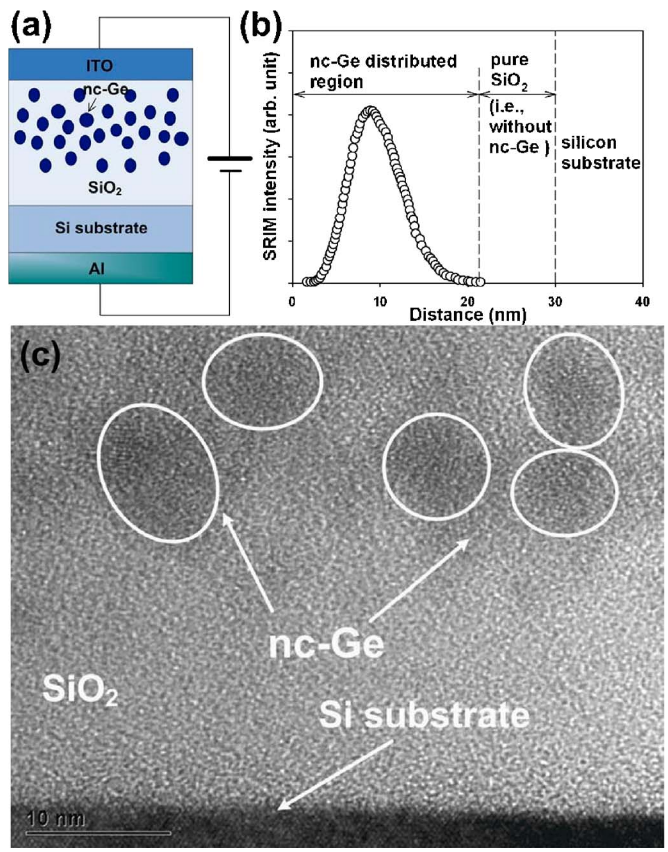

FIG. 1. (Color online) (a) Schematic illustration of the device structure. (b) Distribution of nc-Ge in the gate oxide obtained from SRIM simulation. (c) Cross-sectional TEM image of nc-Ge embedded in SiO_2.

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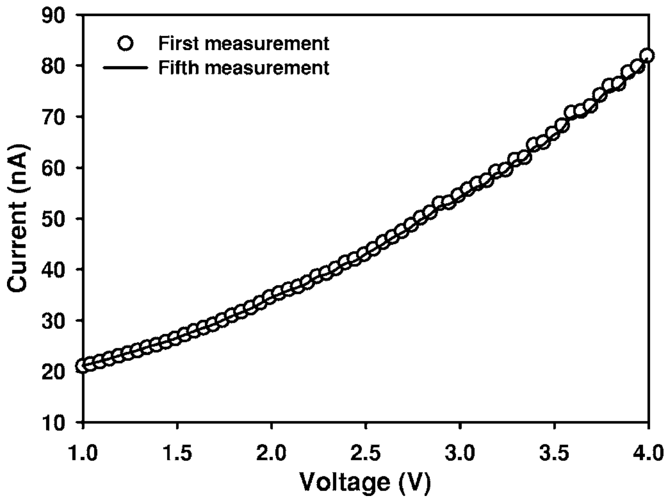

FIG. 2. Repeated current-voltage (*I-V*) measurements without UV illumination.

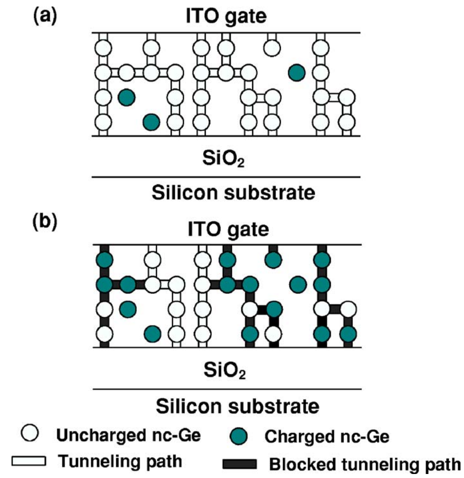

FIG. 4. (Color online) Proposed model of the effect of charging and discharging in nc-Ge on the current conduction of the gate oxide. (a) Conductive tunneling paths formed by uncharged nc-Ge and (b) blocked paths due to charging in nc-Ge.

firmed by cross-sectional transmission electron microscopy (TEM) measurement, as shown in Fig. 1(c). The current-voltage (*I-V*) and time-domain current measurements were conducted with a Keithley-4200 semiconductor characterization system at room temperature. The UV illumination was carried out with an Oriel-66011 arc lamp together with an Oriel-77250 monochromator. The wavelength used for the UV illumination is 365 nm.

Figure 2 shows the *I-V* characteristics of the structure with nc-Ge distributed in the gate oxide before UV illumination. Note that the maximum voltage of the *I-V* measurement is 4 V which is low enough such that no charging/discharging effect occurs due to the electrical measurement itself. As can be seen in Fig. 2, the repeated measurements did not cause a significant change in the *I-V* characteristic. This indicates that no significant charging or discharging in nc-Ge occurs during the *I-V* measurement and the conduction of the gate oxide was not affected by the measurement itself. However, after an exposure to UV illumination, the *I-V* characteristic is found to change drastically. Figure 3 shows the comparison between the *I-V* characteristics before and after the UV illumination for 5 s. As can be seen in this figure, the current is reduced by more than 50% after the UV illumination. The reduction in the current indicates a large

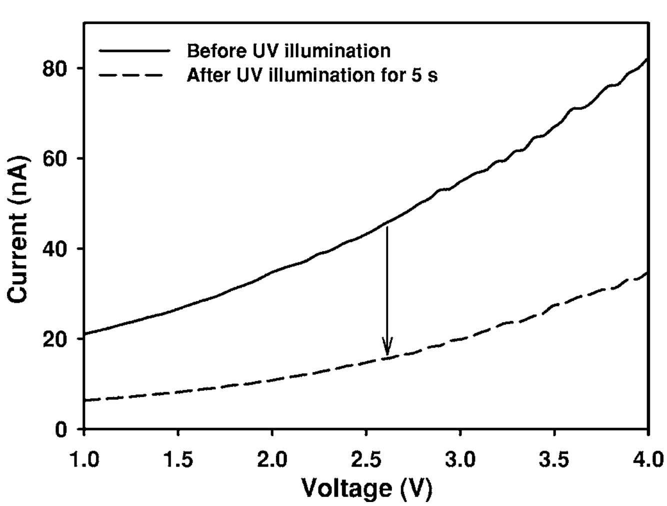

FIG. 3. *I-V* characteristics before and after UV illumination for 5 s.

increase in the dc resistance (or decrease in the conductance) of the gate oxide.

The increase in the dc resistance can be explained in terms of the breaking of some tunneling paths due to charging in some nc-Ge caused by UV illumination. Electron tunneling can take place between adjacent uncharged nanocrystals, and a large number of such nanocrystals in the oxide can form many conductive tunneling paths which significantly increase the conductance of the gate oxide, as shown in Fig. 4(a). However, if some of the nc-Ge is charged, the tunneling paths related to the charged nc-Ge will be blocked due to the Coulomb blockade effect, as shown in Fig. 4(b). As a result of the charging in the nc-Ge, the conductance of the oxide decreases. If the sample is exposed to UV light, some of the electrons generated by the UV illumination could be trapped in the nc-Ge, leading to a reduction in the oxide conductance. At the same time, the UV illumination could cause the release of the trapped electrons from the nc-Ge also, resulting in an increase in the oxide conductance. Charging and discharging in the nc-Ge due to the UV illumination are two competing processes which occur simultaneously. If the charging process is dominant, the oxide conductance is reduced; however, if the discharging process is dominant, the oxide conductance is increased. The two situations have been observed in our experiment. As shown in Fig. 3 an UV illumination for 5 s leads to a large reduction in the oxide conductance; however, a further UV illumination for 200 s results in an increase (a partial recovery) in the conductance as compared to the conductance of the 5 s illumination, as shown in Fig. 5(a). On the other hand, as shown in Fig. 5(b), the oxide conductance can recover almost to the level of the virgin situation after a thermal annealing at 150 °C for 15 min in addition to the UV illumination for 200 s. This indicates that almost all the charges trapped in the nc-Ge due to the first UV illumination can be released after the second UV illumination and the thermal annealing.

As mentioned above, the charging and discharging in nc-Ge could occur simultaneously under UV illumination. This suggests that the conduction of the gate oxide can be modulated by UV illumination in a time-domain measurement at a constant measurement voltage. This is confirmed in our experiment. Figures 6(a) and 6(b) show the time-domain

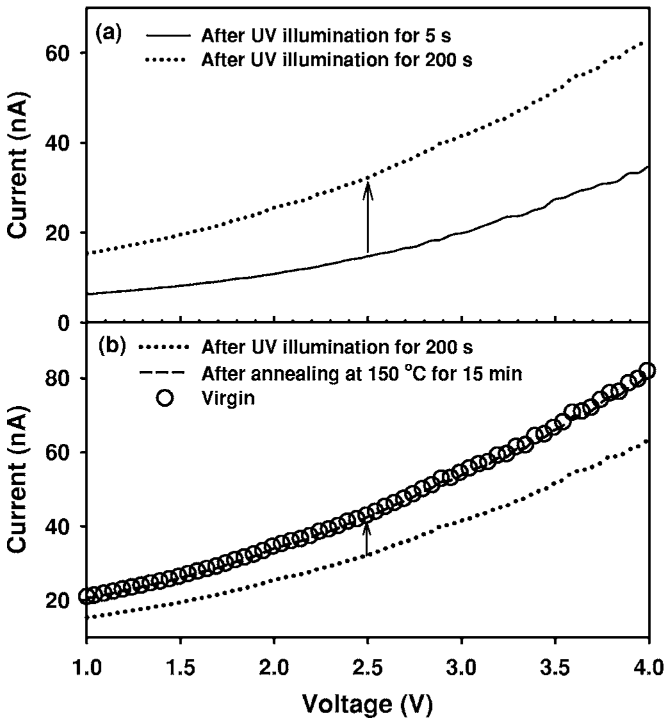

FIG. 5. (a) Partial recovery of the gate current after another UV illumination for 200 s from the situation of the UV illumination for 5 s. (b) Full recovery of the gate current after an annealing at 150 °C for 15 min in addition to the UV illumination for 200 s.

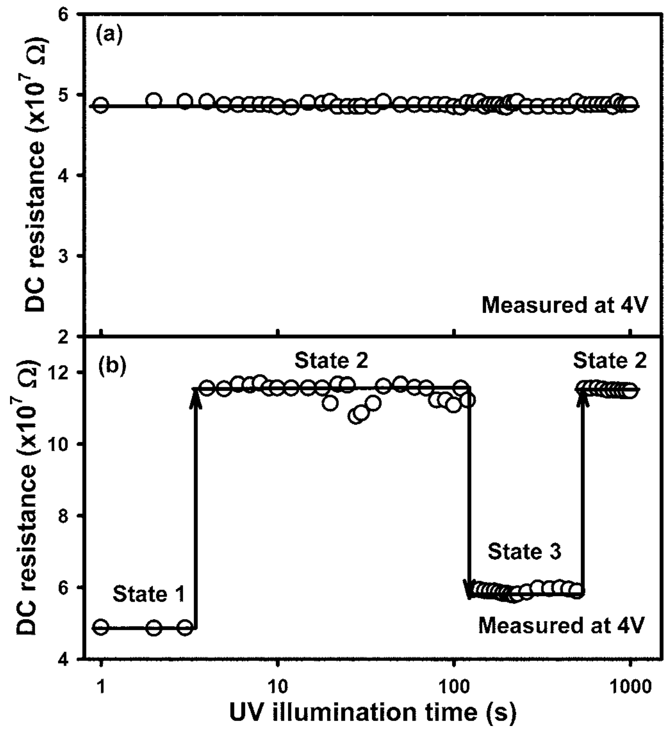

FIG. 6. Time-domain measurement of the dc resistance of the oxide: (a) without UV illumination and (b) with UV illumination. The dc resistance was measured at a gate voltage of 4 V.

dc resistance measurement at 4 V without and under UV illumination, respectively. As can be seen from Fig. 6(a), no significant resistance change is observed, indicating that no significant charging and discharging in nc-Ge occur during the measurement without UV illumination. However, the resistance is modulated under the UV illumination, as shown in Fig. 6(b). As can be seen from this figure, after the first UV illumination for 4 s, the resistance is switched from a low-resistance state (state 1), which corresponds to the situation of no charge trapping in the nc-Ge, to a high-resistance state (state 2) as a result of charging in the nc-Ge due to the UV illumination. State 2 is maintained for about 120 s, and then the resistance is switched to a new state (state 3) which has a resistance much lower than that of state 2 but slightly higher than that of state 1. This indicates that not all of the trapped charges associated with state 2 have been released and thus only a partial recovery of the conduction is achieved. After staying at state 3 for about 370 s, the resistance is switched back to state 2 as the charging process is dominant again. If the time scale is extended, the switching between different states, which is a random event, can be observed continuously. However, it is generally observed that for a virgin sample a short UV exposure leads to a switching to a high-resistance state (i.e., the charging process is dominant) while a further exposure could cause a switching back to a low-resistance state (i.e., the discharging process is dominant) depending on the exposure duration.

In conclusion, we have observed UV-illumination-induced conduction modulation in SiO_2 films embedded with nc-Ge synthesized by ion implantation. The conduction modulation is due to the charging and discharging in the nc-Ge caused by UV illumination. The charging and discharging in the nc-Ge are two competing processes which occur simultaneously. If the charging process is dominant, the oxide conductance is reduced; however, if the discharging process is dominant, the oxide conductance is increased. As the conduction can be modulated by UV illumination, it could have potential applications in silicon-based optical memory devices.

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