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Photo-Induced Electron Charging to Silicon-Quantum-Dot Floating Gate in Metal-Oxide-Semiconductor Memories

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1. Introduction

The implementation of silicon-quantum-dots (Si-QDs) as a floating gate in MOSFETs has been attracting much attention because of its feasibility for multivalued memory operations at room temperature [1-4]. So far, we have fabricated nMOSFETs with a Si-QDs floating gate and confirmed multiple-step threshold voltage shift at room temperature[1,4]. We have also demonstrated that electron charging of the Si-QDs floating gate at constant gate voltages proceeds stepwise through metastable charged states associated with the redistribution of injected electrons [4]. Such unique multistep charging has yet to be studied in details to control precisely discrete charged states in the Si-QDs.

In this work, to gain a better understanding of the mechanism of multistep electron charging of the Si-QDs floating gate, we have studied the influence of light irradiation on electron injection characteristics in Si-QDs floating gate.

2. Experimental

Si-QDs were self-assembled on a 3.3-nm-thick SiO_2 layer thermally grown on p-Si(100) with an acceptor concentration of $1.5x10^{17}cm^{-3}$ by the low-pressure chemical-vapor-deposition (LPCVD) of pure SiH_4. After that a 1-nm-thick thermal oxide layer was grown at 850°C. In order to obtain sufficient dot density, this process was performed once again. The average dot height and the dot density evaluated by AFM were 6nm and $6\times10^{11}cm^{-2}$, respectively. Subsequently, a 3.3-nm-thick amorphous Si layer was uniformly grown on the dot layer by LPCVD of 10% Si_2H_6 diluted with He and fully oxidized in dry 2% O_2 to form a 7.5-nm-thick control oxide. Finally, a 200-nm-thick n^+poly-Si gate and source/drain junction were fabricated. The gate length, width and junction depth are 0.5 - 1.0, 10 and ~1.5μm, respectively.

650nm(1.91eV) and 780nm(1.59eV) lights from semiconductor lasers with photon fluxes of 5 $x10^{16}$~2 $x10^{18}$ (cm^{-2}/s) were used in this work for generation and excitation of carriers in the channel region.

3. Results and Discussion

The temporal changes of drain current (I_D-t) measured at constant gate voltage in dark and under light irradiation were compared as shown in Fig. 1. Although the current level is increased by 1.59eV light irradiation due to the

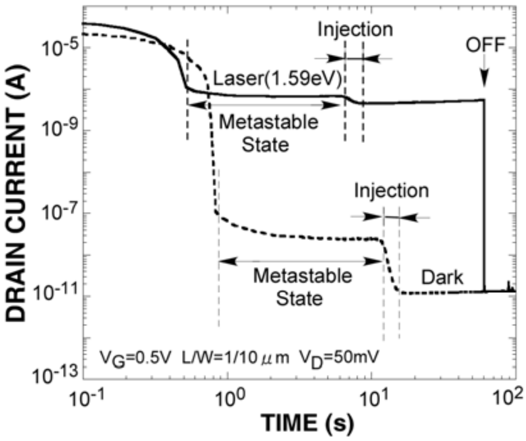

Fig. 1 Temporal changes in the drain current measured at V_G =0.5V under irradiation of 780nm (1.59eV) light and dark condition after complete discharging of the Si-QDs floating gate at V_G =-4V. Electron charging to the Si-QDs floating gate causes the threshold voltage shift resulting in the decrease in I_D.

photogenerated electron contribution, multistep electron charging of the Si-QDs floating gate and a metastable state, in which a slight decrease in the drain current is observable, are still clearly observed as in the case measured in dark. Obviously, 1.59eV light irradiation promotes electron injection to the Si-QDs and reduces the period of the metastable charged state. Notice that when the light irradiation was turned off in the stable state achieved under light irradiation, the drain current coincides with the current level of the stable state obtained in dark. This indicates that the same amounts of charges were injected finally into the Si-QDs floating gate in both cases under light irradiation and in dark condition. In other words, excess electrons over a thermally equivalent level in dark is not injected to the dots under this light irradiation, which implies sufficient energy separation between the charged state and the next. We also found that the electron injection speed at the transition from the metastable charged state to the finally stable charged state was unlikely to be accelerated with increasing photon flux (Fig. 2) and in the photon energy (Fig. 3) although the time to the final stable state became shorter with higher photon flux and/or higher photon energy. The result implies that the light irradiation mainly accelerates the temporal change in the charging during the metastable charged states to trigger the transition to the final stable state.

To get a clear insight into the influence of the light

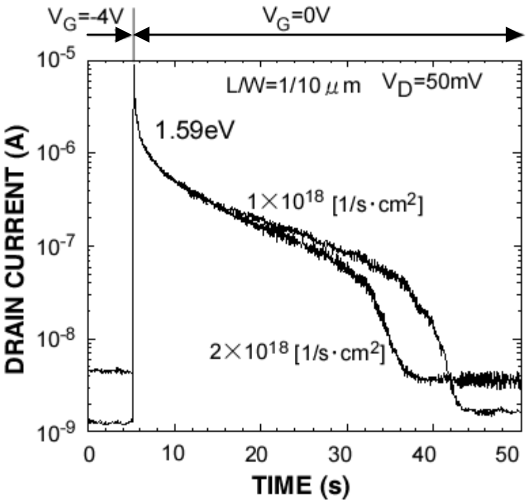

Fig. 2 The temporal changes in the drain current measured at V_G=0V under 1.59eV light irradiation with photon fluxes of 1 x 10^{18}, 2 x 10^{18} cm^{-2}/s after complete discharging of the Si-QDs floating gate at V_G =-4V.

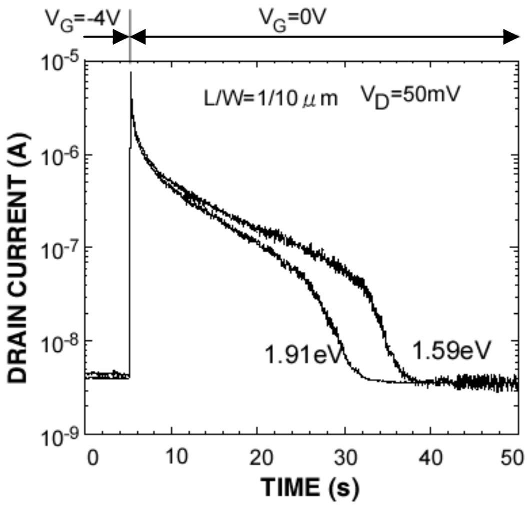

Fig. 3 The temporal changes in the drain current measured at V_G=0V under light irradiation of 1.59eV and 1.91eV photons with the same flux after complete discharging of the Si-QDs floating gate at V_G =-4V.

irradiation on the temporal change in the metastable charged states, the light irradiation was turned off during the I_D-t measurement as shown in Fig. 4. When light irradiation was turned off in the early stages of metastable charged states, the drain current quickly decreased to some current level once and recovered partly due to the electron emission from the dots and then followed by the temporal change in dark. Since the electron emission becomes hardly observed with the time spending in metastable states, the redistribution of electrons in the Si-QDs proceeds during the metastable charged state to further electron injection. Based on these results, we can suggest that the light irradiation plays an important role on the redistribution of electrons in the Si-QDs floating gate.

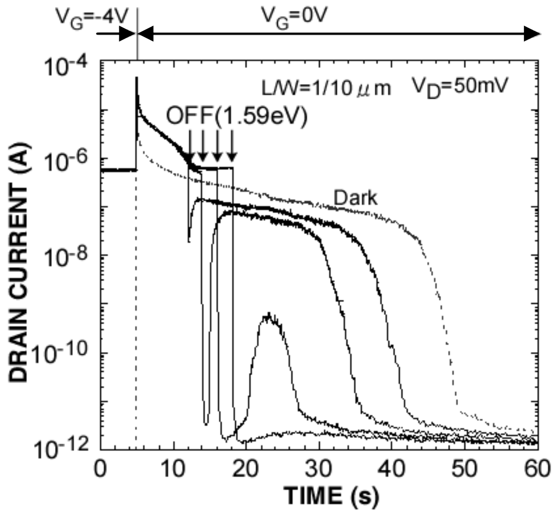

Fig.4 Temporal change in the drain current, which was measured at V_G=0V when the 1.59eV light irradiation was turned off at various time as indicated by arrows. The result obtained without light irradiation anytime is also shown as a reference.

Considering the fact that, by irradiation of photons with a sub-gap energy (0.80eV, 7 x 10^{17} cm^{-2}/s), no significant promotion in electron charging is observable, the contribution of the photoexcitation effect of injected electrons in the Si-QDs to the electron redistribution in the floating gate can be ruled out. The generation of hot electrons in channel with visible light irradiation is thought to be a crucial factor for the shortened metastable state, in which the electron tunneling seems to be controlled by the charging and quantized energy in Si-QDs.

4. Conclusions

We have demonstrated that the electron charging of the Si-QDs floating gate is accelerated by visible light irradiation and the accelerated charging is mainly attributable to the promotion of electron redistribution in the metastable charged states.

Acknowledgements

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