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Function of Porous Silicon Diode as a Light-Emitting Bistable Memory

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1. Introduction

Room-temperature visible photoluminescence (PL) [1] and electroluminescence (EL) [2] from porous silicon (PS) have been discussed in relation to quantum confinement effects, because PS consists of a great number of Si nanocrystallites. The quantum structure of PS should have effects not only on the optical properties but also on the electrical properties. Recently-reported negative-resistance effects [3, 4] in electroluminescent PS diodes reflect the characteristic properties of electrical conduction in PS. This paper reports that RTO-PS diode has a function as an nonvolatile memory device. A possible mechanism for this effect is also discussed.

2. Experimental

The PS layers were formed by anodizing single-crystal nondegenerate p-type Si (100) wafers (resistivity: 2-6 Ωcm) in a solution (55% HF:ethanol=1:1) at current densities of 10 mA/cm^2 for 50-60 sec in the dark. Immediately after anodization, the PS samples were transferred to a vacuum chamber, and rapid thermally oxidized (RTO) at a temperature of 1000 °C for 10-12 min. After the RTO process, Au or indium tin oxide (ITO) films were deposited onto the PS layers. The active area of the PS diodes was 5 mm in diameter.

The current-voltage (I–V) characteristics of the PS diodes were measured under the forward and reverse bias conditions. The EL intensities are also measured at the same time. The forward bias condition corresponds to the case in which a negative voltage is applied to the Au electrode with respect to the Si substrate.

3. Results and Discussion

The I–V curve of the experimental PS diode is shown in Fig. 1. The experimental diode was composed of a semitransparent Au film, a RTO-PS layer (~0.5 μm), a p-type Si and an ohmic contact, as shown in Fig. 1. The diode current shows a significant hysteresis. As the bias voltage is swept from 0 V toward the reverse direction, the diode current density at first remains extremely low (①: off-mode). At a threshold voltage of about ~18 V, however, the diode operation changes from the off-mode to the on-mode(②), and the high diode current begins to flow(③). The on-mode is nonvolatile, and kept at least for one week until the erasing voltage is applied.

The on-mode(④) can be turned to the off-mode when a sufficient forward bias voltage (13 V in this case) is applied. At this point, the high-resistivity state appears again(⑤). These results shows that the RTO-PS diode operates as an nonvolatile memory device, and the reverse and forward bias voltages correspond to the writing and erasing voltages, respectively.

Figure 1 also shows the voltage dependence of the EL intensity. The EL intensity behaves in a similar way to the diode current. Only when the device is at the on-mode, the diode shows the EL emission. Thus the stored information can be read not only by the electrically, but also by optically.

The I–V curve of the RTO-PS diode under the condition that the PS layer was illuminated by a Ar laser (514.5 nm) through the ITO film in the writing process (photo-writing) is shown in Fig. 2 by the solid curve, together with the corresponding EL intensity. In this figure, the result obtained in the dark is also shown by the dashed curve. This RTO-PS diode was composed of a ITO film (200 nm), a RTO-PS layer (~0.6 μm), a p-type Si and an ohmic contact.

After the photo-writing process, read-out current is increased by about one order of magnitude, in comparison with the dark-writing case. The result shows that the RTO-PS can store the photo-induced writing current as an optical information. In addition, the EL intensity was enhanced after the photo-writing process.

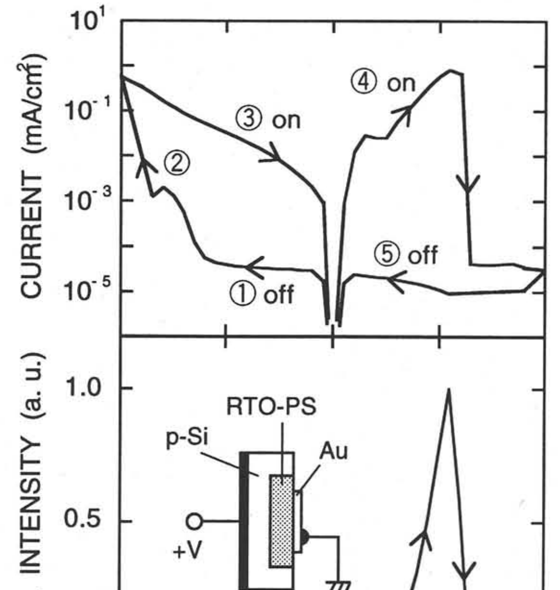

Fig. 1 The I–V curve of a RTO-PS diode and corresponding EL intensity as a function of forward bias voltage. The inset is a schematic illustration of the RTO-PS diode under the forward bias condition.

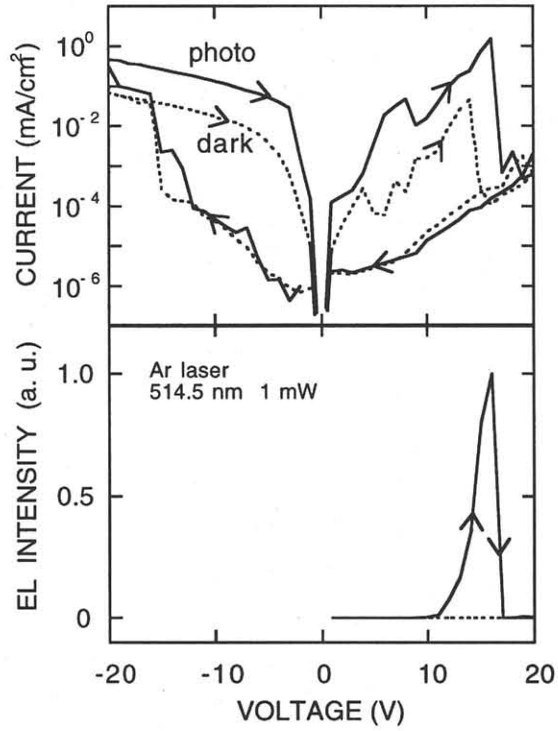

Fig. 2 The I–V curves of a RTO-PS diode in the dark condition (dashed curve) and the condition when the PS layer is excited with a 514.5 nm Ar laser through the ITO film during the writing operation (solid curve) and the corresponding EL intensities as a function of forward bias voltage.

A band model for this memory effect is schematically shown in Fig. 3. The simplified band diagram of the PS diode under the condition that a negative bias voltage is applied to the Si substrate is shown in Fig. 3 ①. The RTO-PS layer consists of a great number of Si crystallites surrounded by some electronic barriers. Such crystallites are shown as cross bars in the PS layer with a widened band gap. Under the low bias voltage, the diode current is extremely low.

The nanoscopic structure of the Si crystallite in the PS under the reverse bias condition is schematically shown in Fig. 3 ②. As the crystallite is surrounded by some electronic barriers, it is connected together via wider-gap interface regions. At a critical reverse bias voltage, the energy position of the valence band edge of a crystallite becomes comparable with that of the conduction band edge of the neighboring one. In this situation, electrons in the valence band of crystallites can tunnel to the conduction band of neighboring ones through thin oxide layers as shown in Fig. 3 ② (a). After the tunneling of the electrons, holes remain in the Si crystallites. As the holes play as a role of fixed charges, the potential distribution is distorted as shown in Fig. 3 ③, and then the high-electric-field near the Si substrate promotes the injection of the electrons from the Si substrate to the PS layer. The injected electrons from the substrate also contribute to the electrical transport, and a significant amount of current begins to flow in the PS diode. This situation corresponds to the on-mode. When the PS layer is illuminated during the writing process, electron-hole pairs are photogenerated in the Si crystallites as shown in Fig. 3 ② (b). Thus the amount of the stored hole in the PS layer is further increased.

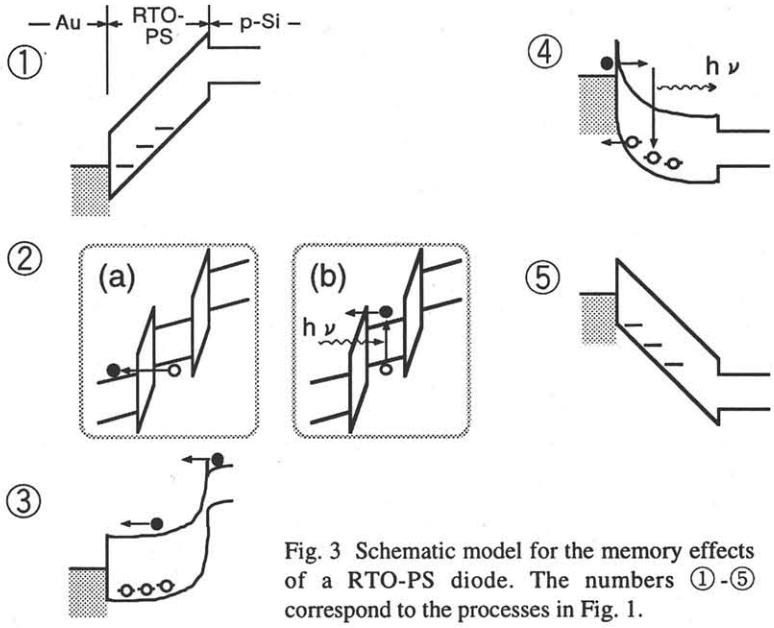

Fig. 3 Schematic model for the memory effects of a RTO-PS diode. The numbers ①-⑤ correspond to the processes in Fig. 1.

When the forward bias voltage is applied to the PS diode at the on-mode, the potential distribution is distorted as shown in Fig. 3 ④, and then the high-electric-field region near the surface leads to the injection of the electrons from the Au electrode to the PS layer. Some part of these electrons contribute to the radiative recombination in the PS. When the sufficient forward bias voltage is applied for erasing signal, the stored holes in the Si crystallites are swept away from PS, and the PS layer returns to the off-mode as shown in Fig. 3 ⑤.

4. Conclusion

Memory effects were observed in EL-emissive PS diodes with a relatively thin RTO-treated PS layer. The devices show stable on- and off-modes which can be controlled by reverse (writing) and forward (erasing) bias voltage. In addition, the signal can be stored and read optically. The function as a nonvolatile memory device in the RTO-PS diodes suggests the possibilities of PS for the optoelectronic devices applications.

Acknowledgements

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