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Negative-Resistance Effects in Light-Emitting Porous Silicon Diodes

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1. Introduction

Detailed analyses about the carrier injection and subsequent transport in luminescent porous silicon (PS) have been carried out in order to understand the mechanism of the electroluminescence (EL) from PS [1] and to develop PS-based optoelectronic devices. As reported previously [2], the EL-emissive PS diodes show some characteristic electrical functions associated with the visible light emission. It closely relates to that the PS layer consists of a great number of silicon nanocrystallites with a widened bandgap. This paper reports a definite negative-resistance behavior observed in EL-emissive PS diodes. Details of this effect are presented in relation to the EL emission characteristics. A possible mechanism and its implication will also be described.

2. Experimental

The PS layers were formed by anodizing heavily doped (~0.018 Ω·cm) n-type (111) silicon wafers in a solution of HF(55%) : ethanol = 1 : 1 at a current density of 50 mA/cm^2 for 1 min under illumination by a 500 W tungsten lamp from a distance of 20 cm. The thickness of the PS layers was about 5 μm.

After anodization, a semitransparent thin Au film (10 nm thick) was evaporated onto the PS layer. The diameter of the active area of the device was 5 mm. The experimental PS diodes were composed of thin Au films, PS, n-type Si and ohmic back contacts, as shown in Fig. 1.

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

3. Results and Discussion

The PS diode exhibits a rectifying behavior. Figure 1 shows the I–V curve in the forward bias region at room temperature and a low temperature of 10 K. The corresponding EL intensity of the PS diode as a function of forward bias voltage are also shown in Fig. 1. At room temperature, the diode current shows a slight decrease beyond a critical forward bias voltage of ~10 V. This negative-resistance effect was reversible. The PVCR (peak-to-valley current ratio) is about 2.

The effect becomes more significant at a low temperature of 10 K, as indicated in Fig. 1. The PVCR value reaches about 10^4. This enhanced negative-resistance effect is related to the electrical property of PS that the tunneling conduction becomes dominant in carrier transport at low temperatures below about 150 K [3].

It is observed that the EL intensity begins to increase at the onset of the negative-resistance. To clarify this situation, the diode current density dependences of EL intensity are plotted in Fig. 2. Obviously, the EL emission is switched on at certain diode currents. The change in the electrical conduction leads to the radiative recombination in PS. This behavior is clearly observed at a low temperature of 10 K.

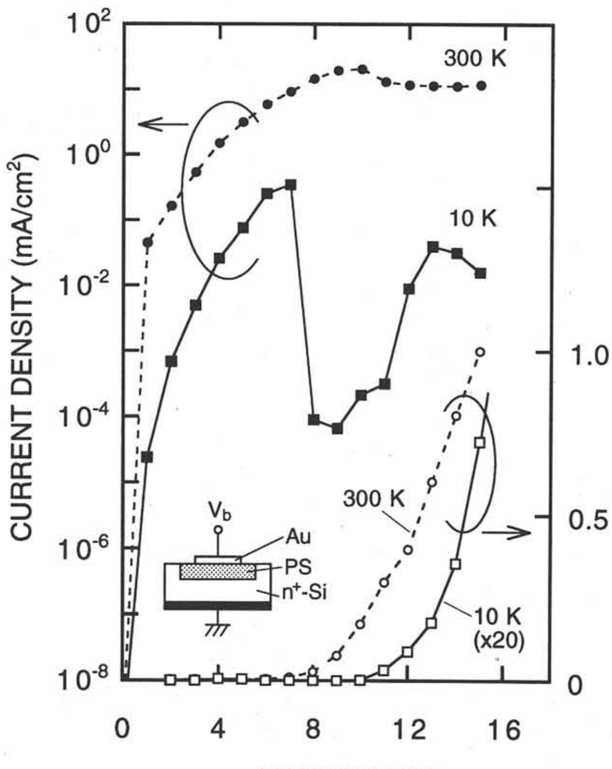

Fig. 1 The I–V curve of a PS diode at room temperature and a low temperature of 10 K and the corresponding EL intensity as a function of forward bias voltage. The inset is a schematic illustration of the sample under the forward bias condition.

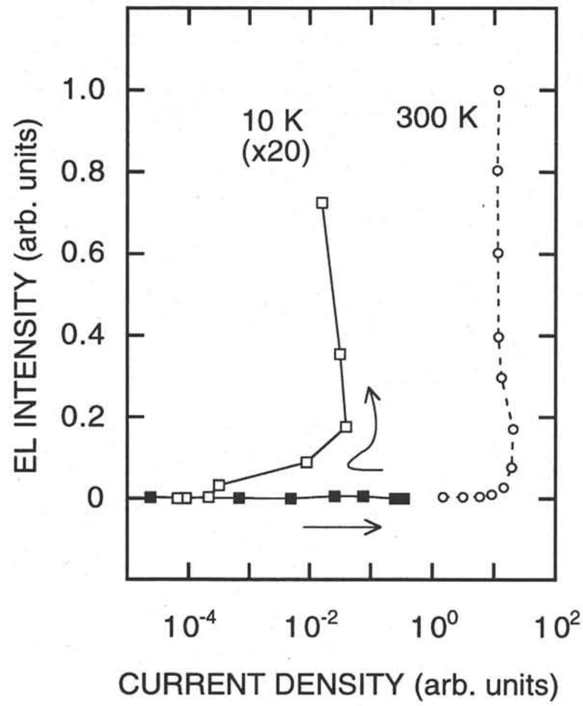

Fig. 2 The current density dependence of the EL intensity obtained from the result of Fig. 1. The voltage-controllable EL emission is switched on at a critical carrier injection.

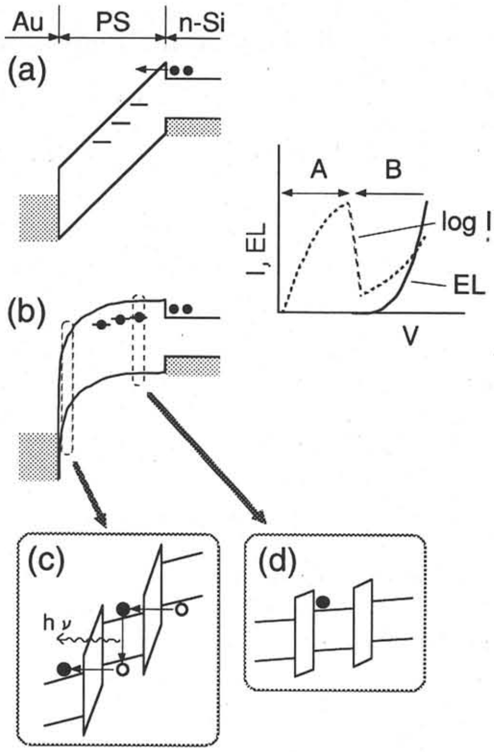

Fig. 3 Schematic model for the negative-resistance effect of a PS diode. The regions A and B in the I–V curve correspond to the band diagram (a) and (b), respectively. Small bars in the bandgap represents the sites of silicon nanocrystallites.

To investigate these peculiar characteristics of the PS diodes, a band model is schematically shown in Fig. 3. The photo-anodized PS layer includes a great number of quantum-sized Si crystallites surrounded by some electronic barriers. Under the forward bias condition, electrons are injected from the Si substrate into the PS layer, and then drifted toward the Au electrode as shown in Fig. 3 (a).

Beyond a critical bias voltage, electrons are injected into the Si crystallites by tunneling. As injected electrons play as a role of fixed charges, the potential distribution along the thickness direction of the PS layer is distorted as shown in Fig. 3 (b). Under this situation, the injection from the Si substrate into the PS layer is suppressed because the electric field at the PS/substrate interface becomes lower.

On the other hand, high-electric-field region near the Au/PS interface makes possible radiative recombination of carriers in Si crystallites through field-promoted hole generation mechanism [4] as shown in Fig. 3 (c): electrons in the valence band of crystallites tunnel to the conduction band of the neighboring ones through thin oxide layers. The remaining holes and injected electrons can recombine radiatively. Thus the EL emission is switched on despite a decrease in the transmittance of carriers through the PS layer. At low temperatures, this effect can be produced at lower critical voltages.

4. Conclusion

Negative-resistance effects were observed in the I–V curve of the EL-emissive PS diodes. The uniform visible EL emission is switched on at the onset of the negative-resistance behavior. The effect becomes more significant at low temperatures. These can be regarded as one of the field-induced functions of PS as a quantum-sized crystalline system. The results suggest the possibilities of PS for the optoelectronic devices applications.

Acknowledgements

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