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Relation between Photoconduction Effects and Luminescent Properties of Porous Silicon

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This work reports the relation between the luminescent properties of porous silicon (PS), its electrical properties, and photoconduction effects. It is shown that the electrical conduction mode in the PS layers at low temperatures is dominated by tunneling either in the dark or under illumination, and that the photoconduction spectra almost coincide with the PL excitation spectra. Reversible field quenching of PL, observed in PS formed on both n- and p-type substrates closely relates to escape of photo-excited carriers. These results confirm that the electronic excitation in Si crystallites play an essential role in the PL process.

1. Introduciton

To explore the luminescence mechanism of PS, it is very important to clarify the relation between the electrical, photoconductive and photoluminescence (PL) properties. Previously, we reported that luminescent PS layers exhibit definite photoconduction (PC) effects in the visible region[1,2] and reversible PL quenching by external bias voltage.[3] In this paper, the detailed information about the relationship between these optoelectronic effects in PS is presented.

2. Experimental

The PS layers were prepared under the following conditions. For measurements of PC effects, the PS layers were formed by anodizing (111) n-type (~0.018 Ωcm) Si wafer in solution of HF (55 wt%) : ethanol (98 %) . Anodization was performed under illumination with a 500 W tungsten lamp from a distance of 20 cm. The anodization current density and time were 100 mA/cm^2 and 5 min, respectively. The thickness of PS layers was 40 μm. For measurements of electrical PL quenching, the PS layers were formed by anodizing (111) p-type (1~2 Ωcm) Si wafer. The anodization time and current density were 10 mA/cm^2 and 30 min, respectively. The thickness of PS layers were 20 μm. After anodization, the PS layers were illuminated with tungsten lamp for 10 min, and then thin Au films (~12 nm thick) were evaporated onto the PS layers. Thus the experimental cell consists of thin Au film, PS layer, c-Si, and ohmic back contact. The PS layer was photoexcited through a semitransparent thin Au film. A positive or negative bias voltage V_b is applied to Au film with respect to the back contact. Besides PL, electroluminescence (EL) characteristics of these samples were also investigated.

3. Results and Discussion

Figure 1 shows the temperature dependence of the dark- and photo-currents at a bias voltage of 50 V. The cell structure is also schematically shown in this figure. At low temperatures, the photocurrent is several orders of magnitude larger than the darkcurrent. The electrical conduction mode at temperatures higher than 150 K is of a thermal-activation type. At low temperatures below 100 K, the conductivity becomes independent of temperature, and the carrier transport is dominated by tunneling. Similar transition can be seen in the electrical conduction under illumination.

The measured PC spectra at 150 K are shown in Fig. 2 as a function of the negative bias voltage. These spectra which peak at about 430 nm can be regarded as the intrinsic spectral photoresponse of PS.[2] A relative increase in the sensitivity in the long wavelength region at high bias voltages is due to the contribution of photocarriers generated in the deeper region of the PS layer to the photocurrent, which suggests that the electric field distribution is not uniform along the depth direction. For the positive bias voltages, on the other hand, there is a larger red shift in the peak wavelength

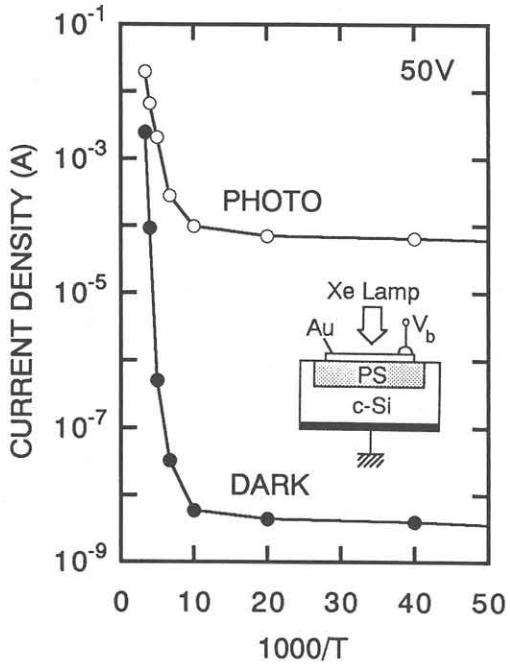

Fig.1 Temperature dependence of the dark- and photocurrents. The inset is a schematic illustration of the experimental PC cell. The incident light intensity was 100 mW/cm^2.

of PC spectra. In this case, carriers generated in both the deep region of the PS layer and the substrate become to contribute to the photoconduction. This result in a large red shift. Anyway, the fact that the photoresponse of PS peaks at ~430 nm confirm the hypothesis of band gap widening in Si crystallites.

In Fig.3, the PC spectrum at 150 K is shown together with the corresponding PL excitation (PLE), PL, and EL spectra at room temperature. Each spectrum is normalized by the respective peak intensity. For PL measurements, a He-Cd laser (325 nm wavelength) was used as an excitation source. The EL spectrum was observed at an applied voltage of 50 V. The PLE spectrum was measured for the PL peak energy. As indicated in Fig.3, the PC spectrum almost coincides with the PLE one. This is a strong indication that excitation for PL occurs in Si crystallites as in the case of PC. Similar results were observed in PS layers formed on p-type substrates as well. A significant energy difference between PL and PLE spectra indicates that there is a strong electron-phonon coupling in the PL emission process. A similarity of the PL spectrum to the EL one verifies that the origin of EL is the same as that of PL.

As shown in Fig.4, the PL emission formed on p-type substrates can reversibly be quenched by the external electric field in a way similar to that from PS formed on n-type substrates. When no bias voltage is applied, the PS layer shows an efficient PL with a peak wavelength of about 650 nm. Under the biased condition, the PL intensity decrease with increasing voltage in either a positive or negative direction. It has been confirmed from measurements of dynamic behavior of PL quenching that the effects of the voltage on PL are completely reversible, and that the response

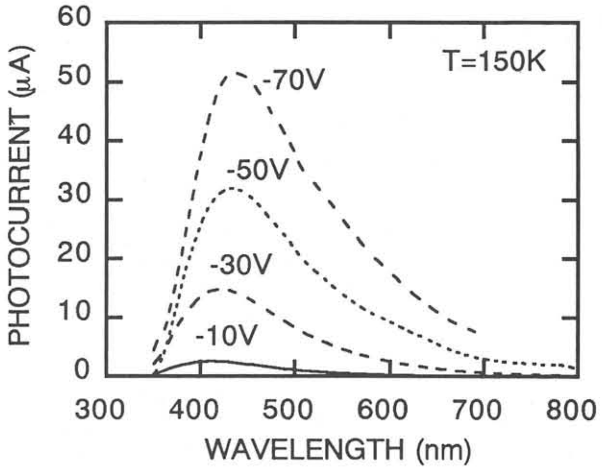

Fig.2 Photoconduction spectra of PS layer as a function of bias voltage. The experimental cell is the same as that used in Fig.1.

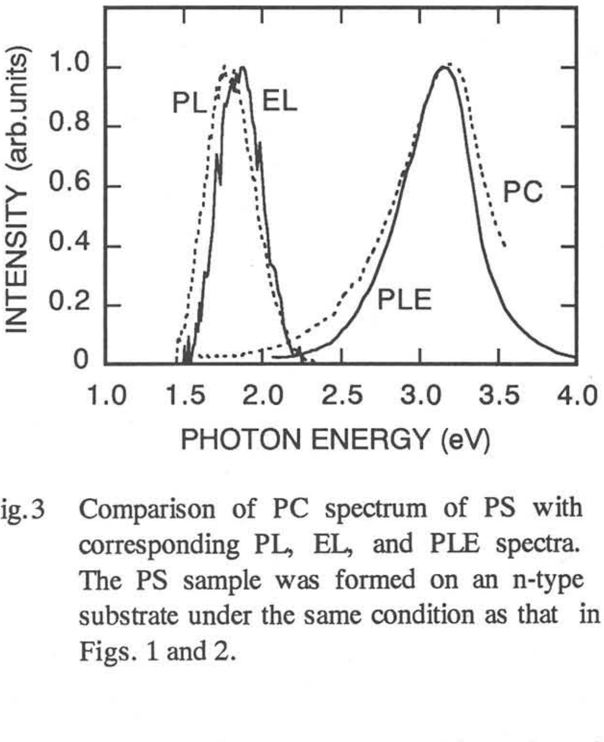

Fig.3 Comparison of PC spectrum of PS with corresponding PL, EL, and PLE spectra. The PS sample was formed on an n-type substrate under the same condition as that in Figs. 1 and 2.

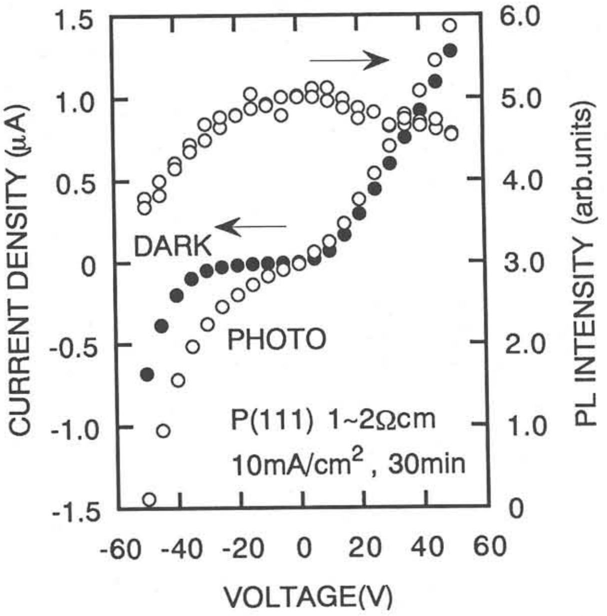

Fig.4 Bias voltage dependence of electrical PL quenching at room temperature. The behavior of dark current is also shown together with that of photocurrent induced by He-Cd excitation for PL measurements.

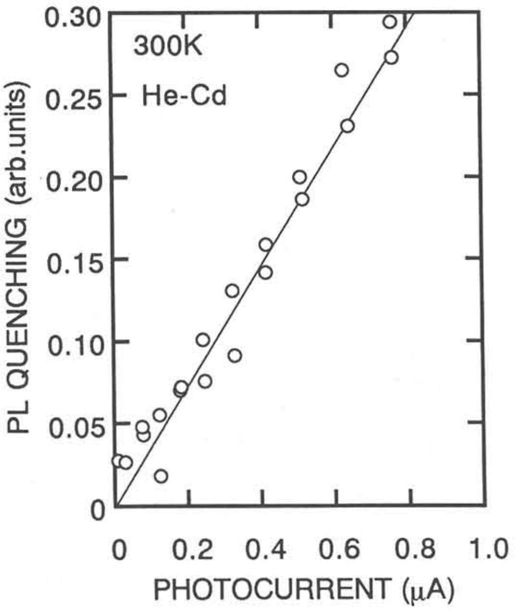

Fig.5 Plots of the change in the PL intensity with increasing bias voltage vs. corresponding net photocurrent induced by He-Cd laser excitation.

time of PL quenching is comparable to the PL decay time. Furthermore, this phenomenon was also observed even at low temperatures of about 20 K. The implication is that the electrical PL quenching is not based on thermal effects, but on field effects.

To provide further support of this explanation, the degree of PL quenching is plotted as a function of the net photocurrent induced by the excitation with a He-Cd laser, as shown in Fig.5. It is evident that the decrease in the PL intensity under either positive or negative bias voltages is proportional to the photocarriers swept away from the PS layer.

Another related issue is the correlation between electrical quenching, PC, and PLE. The efficient field quenching of PL was observed clearly in the samples whose PC spectra are almost the same as the PLE ones. This fact ensures again that photoexcitation for PL and PC occurs in the same place.

4.Summary

There is an important interrelation between PL, PLE and PC. It has also been shown that the mechanism of electrical PL quenching is due to field-induced separation of photogenerated electron-hole pairs. The visible luminescence from PS is thought to be based on the electronic excitation within Si nanocrystallites.

Acknowledgments

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