1.55-μm and infrared-band photoresponsivity of a Schottky barrier porous silicon photodetector

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We have investigated the spectral responsivity of porous silicon Schottky barrier photodetectors in the wavelength range 0.4–1.7 μm. The photodetectors show strong photoresponsivity in both the visible and the infrared bands, especially at 1.55 μm. The photocurrent can reach 1.8 mA at a reverse bias of 6 V under illumination by a 1.55-μm, 10-mW laser diode. The corresponding quantum efficiency is 14.4%.

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Silicon is the most important material for integrated circuits and has the most advanced technology among all semiconductors, but the spectral response of Si is limited to 1.1 μm because of its energy gap. However, the detector materials used in optical fiber communications, at the reduced attenuation wavelength of 1.55 μm, are based on compound semiconductors such as InGaAs and InGaAsP. Consequently, these materials are not directly compatible with Si-based integrated circuits and make communication between the optical fiber and a fully Si-based optoelectronic integrated circuit difficult.

Development of visible electroluminescent porous silicon (PS) devices has made considerable progress[1] since Canham demonstrated bright, visible photoluminescence (PL) at room temperature.[2] PS has many unique characteristics, such as a direct and wide modulated energy bandgap, high resistivity, a large surface-area-to-volume ratio, and the same single-crystal structure as bulk Si. These advantages make it a suitable material for photodetectors. Almost all research on PS photodetectors has been focused on the visible band.[3–5] However, there is relatively strong photoluminescent emission in the infrared band,[6] and this band ought to have a corresponding photoresponsivity. This Letter presents the results of our investigation of the photoresponsivity of Al Schottky barrier PS photodetectors in the visible and the infrared bands, especially at 1.55 μm.

The substrate was a (100)-oriented, 20–30 Ω cm, boron-doped, 550-μm-thick Si wafer. Before anodic etching, an Al ohmic contact was deposited on the back of the wafer and covered with acid-proof wax before the anodic etching. The preparation conditions of PS layers included an anodic current density of 20 mA/cm^2, a HF aqueous concentration of 5%, and an anodic etching time of 15 min. The thickness of the as-anodized PS layer was 6 μm. The characteristics of the PS photodetectors were improved by rapid thermal oxidation at 850 °C for 90 s in an O_2 atmosphere and rapid thermal annealing at 850 °C for 15 s in a N_2 atmosphere.

The structure of the PS photodetector was Al (finger type)/PS/Si/Al (ohmic), and the active area was 18 mm^2.[7] The PL of the PS layer was excited by a HeCd laser and measured by an optical multichannel analyzer. The spectral response of this PS photodetector from 400 to 1700 nm was measured by use of a monochromator driven by a stepping motor and a 100-W halogen lamp as a light source. The responsivity was determined by a calibrated Si photodetector and a calibrated Ge photodetector. The photocurrent of the visible band was excited by a tungsten lamp with an illumination of 24.4 mW/cm^2. The photocurrent for wavelengths longer than 1.1 μm was illuminated with the tungsten lamp with a Si wafer as a filter. A 1.55-μm, 10-mW semiconductor laser diode was used to check the 1.55-μm photoresponse, and a Hewlett-Packard HP-4145B semiconductor analyzer was used for measurement of the $I-V$ characteristics.

Under optimized PS preparation conditions,[7] the photocurrents of the PS Schottky barrier photodetector are 0.8 and 21 mA at reverse biases of 0 and 10 V with 22.4-mW/cm^2 tungsten-lamp illumination. Both the dark current and the photocurrent illuminated by a tungsten lamp have strong dependence on the reverse bias. From the $I-V$ characteristics, the photocurrent is of the order of microamps at zero bias and is believed to be associated with the thin oxide formed under the metal contact after rapid thermal oxidation and rapid thermal annealing treatments. This oxide is estimated to be 5-nm under our experimental conditions.[8] It is sufficiently thick to decrease the tunneling probability of the photocarriers through the oxide layer to the metal contact at zero bias.

The spectral responses of PS photodetector operated at various reverse biases are shown in Fig. 1. The responsivity is quite low at 0 V. However, the

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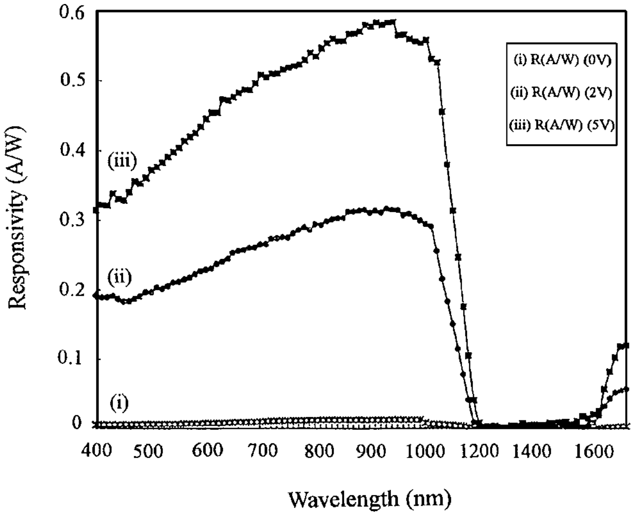

Fig. 1. Responsivity of a PS photodetector at reverse bias of (i) 0 V, (ii) 2 V, and (iii) 5 V.

responsivities are strong in the wavelength ranges 400–1200 nm and 1500–1700 nm at −2 and −5 V. There are no data for wavelengths longer than 1700 nm, owing to the limitations of the measurement system. The responsivity increases with reverse-bias voltage, so the photocurrent is a strong function of bias. The bias dependence could be due to very low carrier velocity that results from the very low carrier mobility (of the order of 10^{-4} cm^2 s^{-1} V^{-1}).[9] Under −5-V bias, the quantum efficiencies at 400, 900, 1100, and 1700 nm are 97%, 80%, 45%, and 10%, respectively. There is, indeed, a high photoresponse in the infrared band. The high quantum efficiencies come from a very high surface-area-to-volume ratio, of the order of 200–800 m^2/cm^3 of porous Si.[10] The photoresponse increases with wavelength in the range 1500–1700 nm. The PL examination of the PS layer shows the same trend as that of the photoresponse in the range 1500–1700 nm, as shown in Fig. 2.

The surface has a significant silicon oxide fraction after preparation in the aqueous solution and annealing by rapid thermal oxidation and rapid thermal annealing. The dominant defect in PS is the dangling bond center P_{bo} at the Si/SiO_2 interface, which is well characterized by electron paramagnetic resonance.[11] In crystalline Si, dangling bond-related emission is nonradiative. However, in small crystalline Si, the dangling bond-related emission becomes radiative. In addition, the spectral intensity of the optically detected magnetic resonance measurements also increases with wavelength in the same infrared band.[12] In other words, the density of the dangling bond center P_{bo} is higher deeper in the energy gap. Therefore the photoresponse increases with wavelength in the infrared band.

We reexamined the responsivity of the infrared band, especially at 1.55 μm. The dark current is ~5 μA at −10 V, as shown in curve (a) of Fig. 3, which is also shown enlarged in the inset. A Si wafer was used to filter wavelengths shorter than 1.1 μm of the tungsten lamp. The $I-V$ curve is shown by curve (b) of Fig. 3. The photocurrent can reach 0.28 mA at −6 V. The current shows a strong photoresponse at wavelengths longer than 1.1 μm. When a 1.55-μm, 10-mW laser diode was used as the optical source, it produced the $I-V$ curve of the PS photodector shown in curve (c) of Fig. 3. The photocurrent can reach 1.8 mA at −6 V. The corresponding quantum efficiency [calculated from 1240/wavelength (nm) × responsivity (mA/W)] at −6 V can reach 14.4%.

The quantum efficiency versus illumination power under 1.55 -μm semiconductor laser diode illumination with the bias voltage as a parameter is shown in Fig. 4. The quantum efficiency is almost a linear function of the illumination power. In addition, the quantum efficiency increases and gradually saturates with reverse-bias voltage.

The photoresponse versus illumination power with a 4.8-kΩ resistor load under 1.55-μm semiconductor laser diode illumination is shown in Fig. 5. The photocurrent increases linearly with illumination power and saturates gradually at a power of 6 mW under reverse bias of 9.92 V. The photocurrent is almost half that at the same illumination power under reverse bias of 4.96 V. The time response of

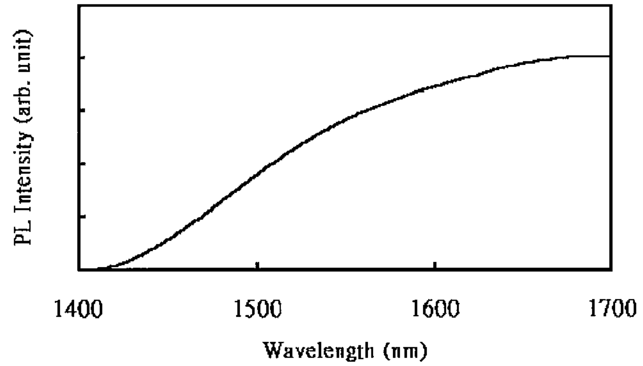

Fig. 2. PL of the PS layer in the range 1400–1700 nm.

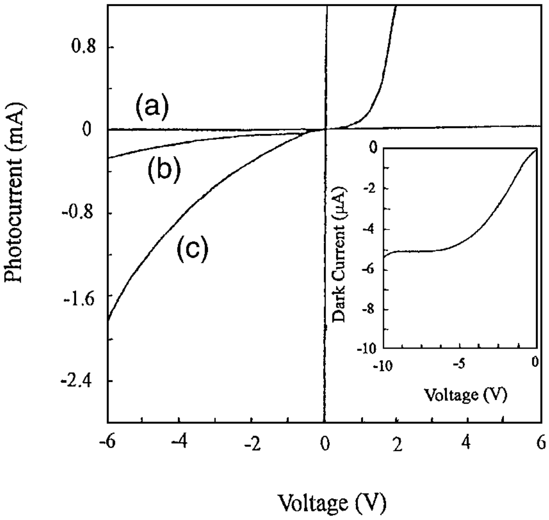

Fig. 3. (a) Dark current of the PS photodetector. (b) Photocurrent with a Si filter under 22.4-mW/cm^2 tungsten-lamp illumination. (c) Photocurrent under 1.55-μm, 10-mW laser diode illumination.

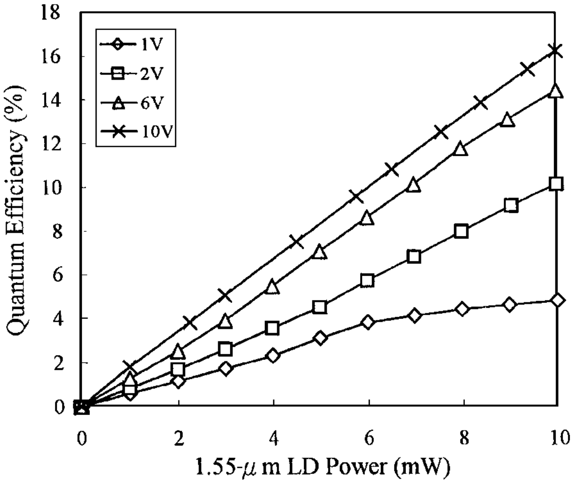

Fig. 4. Photoconductive gain versus illumination power of a 1.55-μm laser diode (LD) with the bias voltage as a parameter.

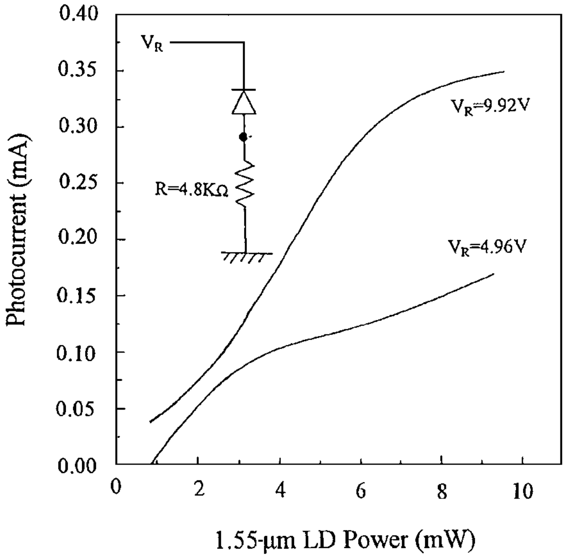

Fig. 5. Photocurrent versus illumination power of a 1.55-μm laser diode (LD) with a 4.8-kΩ resistor load.

the photodetector was also examined with the same circuit. The frequency response was 200 MHz under the present preparation conditions. The frequency response could be limited by the low carrier mobility.[9]

Porous Si has been used successfully in the fabrication of a low-cost, high-sensitivity, wideband photodetector. The Al Schottky barrier porous Si photodetector shows high photoresponsivity in the visible and the infrared bands, especially at 1.55 μm. The bias dependence of the responsivity indicates that photoconductive gain is involved. It has potential to be used in communications between the optical fiber and Si-based optoelectronic integrated circuits.

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