Microstructured silicon photodetector

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Photodetectors fabricated on microstructured silicon are reported. The photodetectors exhibited high photoresponse; at 3 V bias, the responsivities were 92 A/W at 850 nm and 119 A/W at 960 nm. At wavelengths longer than 1.1 μm, the photodetectors still showed strong photoresponse. A generation-recombination gain mechanism has been proposed to explain the photoresponse of these photodiodes. From measurements of the noise current density, the calculated gain was approximately 1200 at 3 V bias. [DOI: 10.1063/1.2227629]

Silicon-based photodetectors are attractive owing to their monolithic integratibility with low-cost complementary metal oxide semiconductor (CMOS) technology. Conventional silicon (Si) photodetectors achieve high responsivity at wavelengths shorter than 850 nm.[1] For longer wavelengths, the absorption coefficient of Si is less than 10^3 cm^{-1}. In order to increase the responsivity, a long absorption region is required. The band gap of Si limits operation to wavelengths <1.07 μm, which makes it unsuitable for many near-infrared applications. In order to extend the operating wavelength of Si-based photodetectors, germanium (Ge) on Si photodetectors and wafer bonded photodetectors on Si substrates have been reported and have achieved high responsivity and high speed.[2–4] Recently, laser-etched microstructured Si has been developed. This material exhibits low reflectance and high absorption across a broad wavelength spectrum extending to 2 μm.[5–9] These properties could extend the application potential for Si-based optoelectronic devices and make them attractive for applications such as infrared imaging, infrared microbolometers, and biomedical and chemical sensors.[10–12] In this letter, photodetectors fabricated with microstructured Si are reported. These photodetectors exhibit high photoresponse in a wide spectral range (600 nm $<\lambda<$ 1100 nm). Photoresponse at 1.31 and 1.55 μm was observed as well.

The device structure was prepared by irradiating n-doped Si (111) wafers (ρ=8–12 Ω cm) with a regeneratively amplified Ti:sapphire laser that delivered a 1 kHz train of 100 fs laser pulses at normal incidence in a 6.7×10^4 Pa atmosphere of sulfur hexafluoride (SF_6). The laser pulses were focused by a 0.25 m focal length lens and struck the silicon surface with an average fluence of 4 kJ/m^2. The experimental setup was described in Ref. 9. Irradiation creates an array of structures on the sample surface only in the region illuminated by the laser. In order to structure an area larger than the laser spot size, the Si substrate was translated relative to the laser beam at a speed such that any given spot on the surface was exposed to an average of 200 laser pulses. Following irradiation, the sample was thermally annealed at 825 K in vacuum for 30 min. This resulted in a surface covered with microstructures that were 2–3 μm tall and spaced by 2–3 μm. The shape of the pillars depends heavily on the scanning conditions such as laser fluence, shot number, gas pressure, gas species, and pulse duration.[6,13,14] Figure 1 is the scanning electron microscope (SEM) picture of the microstructured surface. The surface layer was heavily doped with sulfur, approximately 1 at. %. The microstructured layer has higher doping concentration due to the fact that sulfur can act as a dopant in the laser-etched layer. Hall measurements

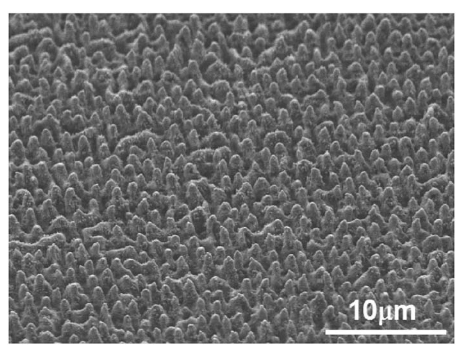

FIG. 1. Scanning electron micrographs of microstructured Si surface.

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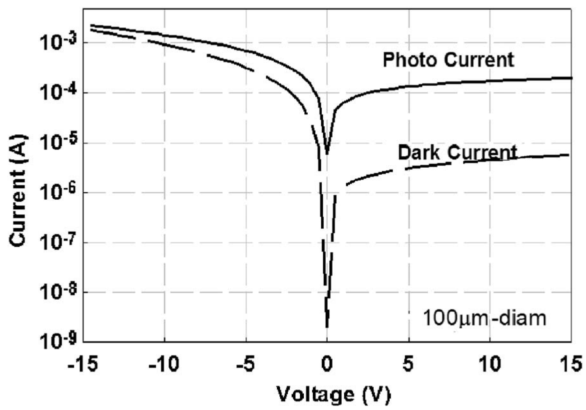

FIG. 2. Photocurrent and dark current vs voltage characteristics for a 100-μm-diam microstructured Si photodetector.

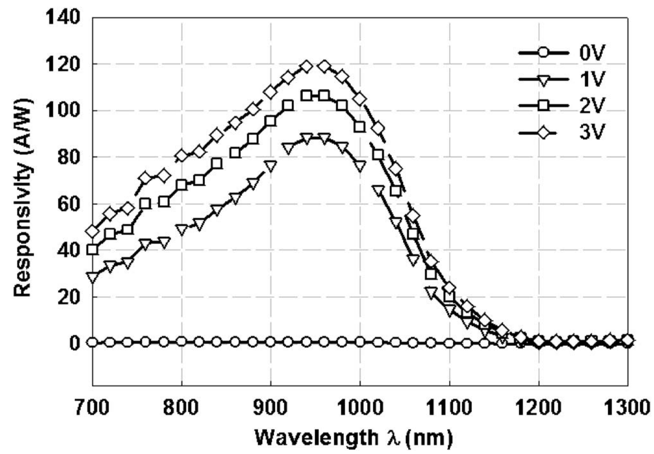

FIG. 3. Responsivity for a 250-μm-diam device under reverse bias of 0, 1, 2, and 3 V.

of this surface layer showed a higher electron concentration than the substrate and electron mobility on the order of 100 $cm^2 V^{-1} s^{-1}$. Laser irradiation thus creates an n/n^+ heterojunction between the undisturbed crystalline substrate and the disordered surface layer.[9]

The wafer was fabricated into mesa devices by lithography, etching, and metallization processes. Mesas having diameters from 50 to 500 μm were wet etched by polysilicon etchant down to the Si substrate and were passivated with 200 nm of SiO_2 by plasma enhanced chemical vapor deposition (PECVD). Ti/Au (35 nm/125 nm) metal contacts were deposited by e-beam evaporation. The contact on the n-type Si substrate is Schottky, while on the microstructured silicon it is Ohmic.

Figure 2 shows the dark current and the photocurrent versus voltage characteristics for a 100-μm-diam device. Between the n-type silicon and its metal contact, a metal-semiconductor Schottky barrier is formed. In this case, reverse bias is defined with the n-type Si substrate biased negative with respect to the microstructured Si. At 1 and 3 V reverse bias, the dark currents were 1.3 and 2.3 μA for a 100-μm-diam device, respectively. This was more than one order of magnitude lower than the forward-biased dark current at the same voltages. The resistivity of the microstructured Si is estimated to be 0.17 Ω cm using the transmission-line method. The capacitance was ~0.2 pF at 1 V reverse bias. When the device was illuminated, the microstructured Si exhibited high photoresponse at near-infrared and visible wavelengths.

The responsivity from 0.60 to 1.60 μm was measured using a tunable monochromatic light source, a lock-in amplifier, and a calibrated Ge photodetector. A tungsten-halogen lamp filtered by a grating monochromator provided a tunable optical input. The responsivity of the photodetector under test was determined by comparing its photocurrent with that from a calibrated photodiode. The incident light was focused to a spot that was smaller than the active area of the photodetector. For wavelengths longer than 1.1 μm, a filter was used to remove higher order short wavelengths. Figure 3 shows the responsivity versus wavelength from 0.60 to 1.30 μm at 0, 1, 2, and 3 V reverse bias. Semiconductor lasers were used to measure the photoresponse at 1.31 and 1.55 μm. At 0 V, the photodetector exhibited low responsivity; however, when the photodetector was biased above 0.5 V, a high photoconductive response was observed. At 850 nm, the responsivities were 0.77 A/W at 0 V and 60, 79, and 92 A/W at 1, 2, and 3 V reverse bias, respectively. At 960 nm, the responsivities were 0.63, 88, 106, and 119 A/W at 0, 1, 2, and 3 V reverse bias, respectively. The responsivities were 0.09 and 0.02 A/W at 1.31 and 1.55 μm, respectively. The ambient gas has an important effect on the photoresponsivity. During laser irradiation the component species of the ambient gas are implanted into the silicon surface in large concentrations. In the case of SF_6, sulfur implantation is extremely important for the high photoresponsivity. Using other gases such as air, nitrogen, and hydrogen does not give the high responsivity. It has been found that selenium and tellurium incorporation also leads to the high photoresposivity.[9] However, these are difficult to use in gaseous form and thin films of each have to be evaporated onto a silicon substrate and then irradiated with the laser.

Figure 4 shows the frequency response of a 250-μm-diam device as determined by illumination through a chopper, whose frequency was varied. The bandwidth of the device was approximately 1200 Hz at 3 V reverse bias, and it did not vary much with device area.

In order to aid identification of the gain mechanism, the noise current density of the microstructured Si photodetector was measured with a low noise current preamplifier and a fast Fourier transform (FFT) spectrum analyzer. Figure 5(a) shows the noise current density versus frequency for a 250-μm-diam device at 3 V reverse bias with photocurrents of 0, 2, and 16 μA, respectively. The noise spectral density of the detector was obtained by subtracting the noise floor of the

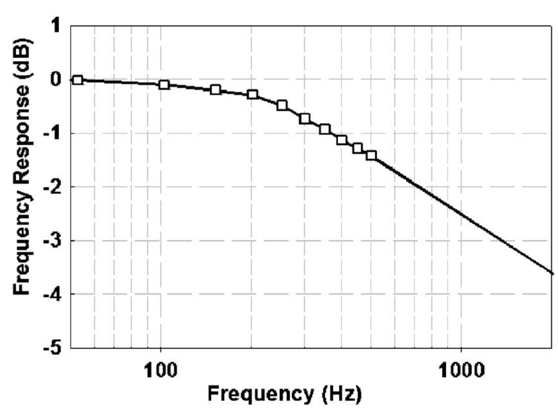

FIG. 4. Frequency response of a 250-μm-diam microstructured Si photodetector at 3 V reverse bias.

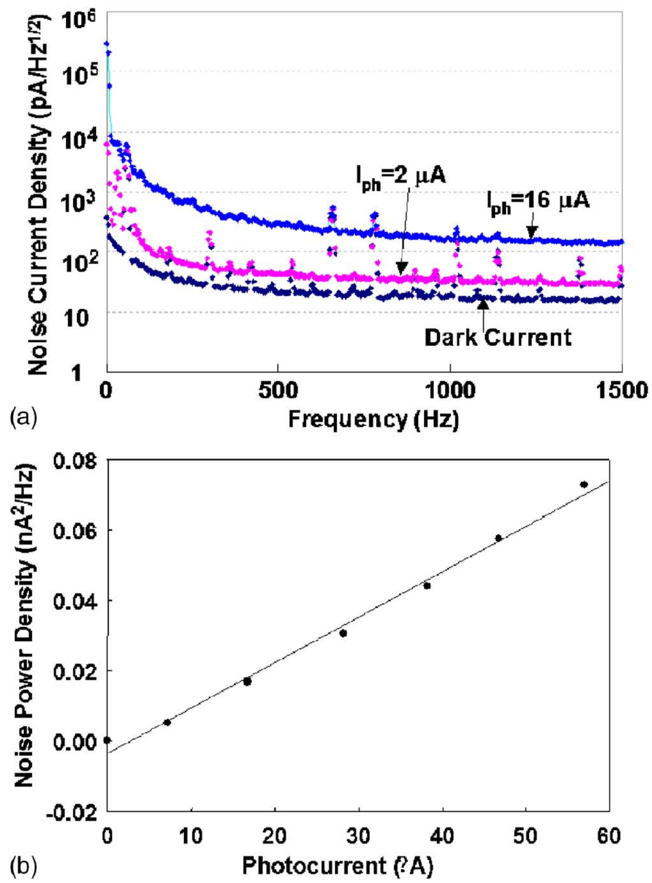

FIG. 5. (a) Noise current density vs frequency at 3 V reverse bias for a 250-μm-diam device with 0, 2, and 16 μA photocurrent. (b) Noise power density vs photocurrent at 3 V reverse bias.

test apparatus from the measured noise spectral density.[15] At low frequency to 100 Hz, the dominant noise was $1/f$ noise. However, at higher frequency, the noise current density was relatively insensitive to frequency, which is consistent with a generation-recombination gain mechanism. From the current noise density, the generation-recombination gain can be estimated. To good approximation, the photodetector gain and the noise gain are equal in a conventional photoconductor. The generation-recombination noise current can be expressed as $i_{GR}{}^2=4IeG\Delta f$, where I is the current and G is photoconductive gain. Using this relation, the extracted noise power density versus photocurrent is shown in Fig. 5(b); the gain was estimated to be 1200 at 3 V bias. From the measurement of noise current, we can also estimate the bandwidth of these devices. The estimated bandwidth is approximately 800 Hz which is consistent with that from the speed measurement discussed above.

In microstructured Si photodetectors, the gain mechanism is most likely to be generation-recombination that originates from random carrier generation and recombination in the high density of impurities and structural defects in the microstructure layer. The high infrared absorptance mechanism in the microstructured Si has been analyzed by Wu *et al.*[5] Sulfur impurities introduce energy states into the band gap of silicon, both near the band edge and in the middle of the band gap. In addition, the structural defects introduce infrared-absorbing states near the band edge. These energy states serve as trapping centers for photogenerated electron-hole pairs. Such band characteristics can explain the observed below-band-gap carrier generation. In the microstructured photodetector, the photogenerated electrons and holes move in opposite directions under applied bias. For example, under reverse bias, photogenerated electrons move toward the microstructured Si surface and holes toward the Si substrate. The resulting photocurrent will persist until both carriers are collected at the electrodes, or until they recombine in the bulk of the semiconductor before reaching the respective contacts. The recombination time of the minority holes is important. During transport to the cathode, they are more likely to be temporarily trapped and reexcited without recombination in the trapping centers.[16,17] At the same time, most electrons, as majority carriers, can travel to the anode within the dielectric relaxation time. The transit time differences between electrons and holes create a large photoconductive gain in microstructured photodetectors. As for all photoconductors, high gain is achieved at the cost of low bandwidth.

We have fabricated laser-microstructured Si photodetectors. The responsivities were 92 A/W at 850 nm and 119 A/W at 980 nm at 3 V reverse bias. At 1.31 and 1.55 μm, the photodetectors still exhibited photoresponse. The noise current density spectrum indicates a generation-recombination gain mechanism for these photodetectors.

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