High sensitivity silicon-based VIS/NIR photodetectors

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Abstract:
We fabricate silicon-based photodiodes using a simple femtosecond-laser microstructuring technique. The detectors are ten times more sensitive than commercial silicon PIN photodiodes at visible wavelengths and can be used at wavelengths up to 1650 nm.
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Silicon is the most commonly used semiconductor in microelectronics and optoelectronic devices but a band gap of 1.07 eV limits the photoresponse to wavelengths shorter than 1100 nm. Consequently, silicon photodetectors are insensitive to the two primary telecommunications wavelengths, 1300 nm and 1550 nm. Therefore, extending the sensitivity of silicon-based photodetectors to longer infrared wavelengths is an active area of research [1, 2, 3].

We previously reported that silicon surfaces microstructured in the presence of sulfur containing gases with high-intensity femtosecond laser pulses have near-unity absorption from the near-ultraviolet (250 nm) to the near-infrared (2500 nm)[4, 5]. Here we report that under reverse bias, these microstructured surfaces can be used to fabricate photodiodes that are sensitive to infrared wavelengths up to 1650 nm and that have greatly enhanced photoresponse to visible wavelengths.

We irradiate n-doped, Si (111) wafers ($\rho = 800$–$1200\ \Omega \cdot \mathrm{cm}$) with a 1-kHz train of 100-fs laser pulses at normal incidence in an 0.67-bar atmosphere of SF_6. Each pulse has an average fluence of 4 kJ/m^2 and a 1/e spot size of 150 x 150 mm^2. In order to structure an area larger than this spot size, the silicon wafer is translated relative to the laser beam at a speed such that any given spot on the surface is exposed to an average of 500 pulses. The resulting surface is covered with conical microstructures that are 2–3 μm tall and spaced by 2–3 μm; the uppermost few hundred nanometers of the microstructures are modified, with crystalline silicon beneath [6].

Following laser irradiation, samples are annealed in flowing argon gas for 30 minutes at 800 K. Electrical contacts are then fabricated by thermal evaporation of a 4-nm layer of chrome followed by a 100-nm layer of gold on both the structured and unstructured sides. Metal is deposited on the entire unstructured side; on the microstructured side, metal is deposited in two circular areas 1 mm in diameter and 3 mm apart center-to-center. The resulting devices have a 2×4 mm^2 active area. Figure 1 shows a schematic diagram of a vertical cross-section through the device and a bright-field transmission electron micrograph of a cross-section of the interface between the laser-affected surface layer.

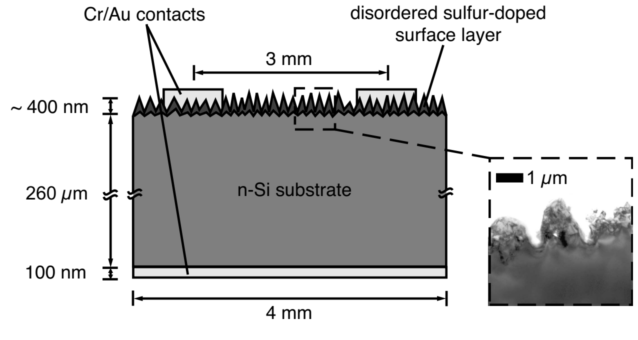

Fig. 1. Schematic diagram of a vertical cross-section through the microstructured silicon photodiode. The dashed box shows a bright-field transmission electron micrograph of the interface between the disordered layer and the crystalline silicon substrate.

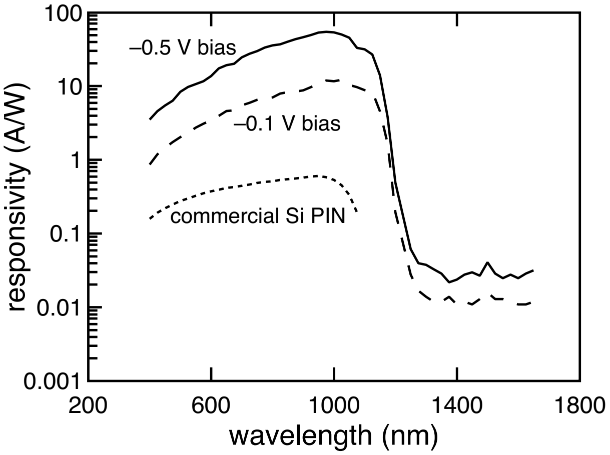

Fig. 2. Spectral responsitivity (wavelength dependence of photocurrent per unit incident power) of microstructured silicon photodiode at a bias of –0.1 V and –0.5 V. The spectral responsivity of the silicon photodiode used for calibration is also shown.

Figure 2 shows the spectral responsivity of the microstructured silicon at a bias of –0.1 V and –0.5 V as well as the responsivity of the standard silicon PIN photodiode used for calibration. At a bias of –0.1 V, the responsivity of the device is greater than 1 A/W for wavelengths from 400 nm to 1175 nm, with a peak responsivity of 12.1 A/W at 975 nm. These responsivities are nearly ten times greater than those of commercially available silicon PIN photodiodes. At longer wavelengths (1200–1650 nm), the responsivity is weaker, but still remarkably high for silicon based devices. For a bias of –0.5 V bias, the responsivity is 38 mA/W at 1300 nm and 25 mA/W at 1550 nm – four orders of magnitude higher than responsivities measured in silicon avalanche photodiodes before amplification [7].

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