High-efficiency and high-speed silicon metal–semiconductor–metal photodetectors operating in the infrared

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A silicon metal–semiconductor–metal photodetector with high-efficiency and high-speed in the infrared is reported. The high performance is achieved by using a Si-on-insulator substrate with a patterned nanometer-scale scattering reflector buried underneath a 170-nm-thick Si active layer. This scattering reflector causes light to be trapped inside the thin Si active layer, resulting in a fast and efficient carrier-collection by the electrodes. The impulse response of the photodetector, measured by electro-optic sampling at 780 nm wavelength, has a full width at half-maximum of 5.4 ps, corresponding to a 3-dB bandwidth of 82 GHz. At both 633 and 850 nm wavelengths, the responsivities of the photodetector with the buried backside reflector are at least an order of magnitude larger than those without the reflector. *© 1997 American Institute of Physics.* [S0003-6951(97)01806-8]

During the past decade, there has been extensive research on metal–semiconductor–metal (MSM) photodetectors on crystalline silicon for use in optical fiber communication and high speed digital chip-to-chip interconnection.[1–13] The impetus for investigating photodetectors on crystalline Si comes from its cost-effectiveness and capability of integration with high-performance electronics through very large scale integrated (VLSI) compatible processes. The latter is even more salient since soon optical fiber communication and signal interconnection will require photoreceivers operating in a 100-GHz frequency region, which in turn requires electronic circuitry, such as preamplifiers, to be integrated with the photodetector monolithically to preserve the desired bandwidth. On the other hand, the wide availability of GaAs lasers has made 800–850 nm the preferred operating wavelength for short-distance signal communication. In this wavelength range, however, Si has severe disadvantages—its light absorption length is considerably long ($\sim 15\ \mu$m). The long absorption length causes a large portion of carriers to be generated far below the depletion region of a MSM photodetector. These deep carriers are collected by the electrodes through diffusion rather than drift, resulting in a reduction in the detector's speed.[6,8] Therefore, in order to achieve high speed Si MSM photodetectors operating in the infrared, the deep-carrier generation has to be eliminated.

To solve this problem, substrates with thin active layers were proposed.[6] Figure 1 compares the carrier transit-time and diffusion-time in a MSM photodetector, calculated from a one-dimensional Monte Carlo model and the diffusion equation.[9] As shown in the figure, to make the diffusion time comparable to the transit time, the active layer thickness should be restricted between 100 and 200 nm. Previously, 200-nm MSM photodetectors on Si-on-sapphire (SOS) with a 500-nm-thick active layer[8] and 100-nm MSM photodetectors on Si-on-insulator (SOI) with a 100-nm-thick active layer[9] have been reported having time responses in full width at half-maximum (FWHM) of 5.7 and 3.2 ps, respectively, in the infrared. However, there is a severe trade-off in using thin active layer—the efficiencies of these detectors are more than an order of magnitude lower than that of those on bulk substrates, since only a small part of the light is absorbed. Recently, Levine *et al.*[11] and Lee *et al.*[12] have demonstrated that roughening the front surface or the backside of the active layer would cause the trapping of light inside the active layer through random scattering, thereby enhancing the efficiency of the MSM photodetector. However, both the demonstrated fabrication techniques (i.e., etching the front or the back surfaces of the Si layer) were unable to control the active layer thickness into the deep-submicron scale, which is required to achieve picosecond responses as demonstrated in Fig. 1. The reported time responses were, respectively, 200 ps at 880 nm wavelength and 74 ps at 830 nm wavelength, which are an order of magnitude larger than that of those on SOS and SOI.

In this letter, we present a novel Si MSM photodetector with substantially high absorption and speed in the infrared. The structure of the device is shown in Fig. 2. Its deep-submicron interdigitized electrodes (fingers) are formed on a SOI substrate with a 170-nm-thick Si active layer. On the bottom of the active layer is a scattering buried backside

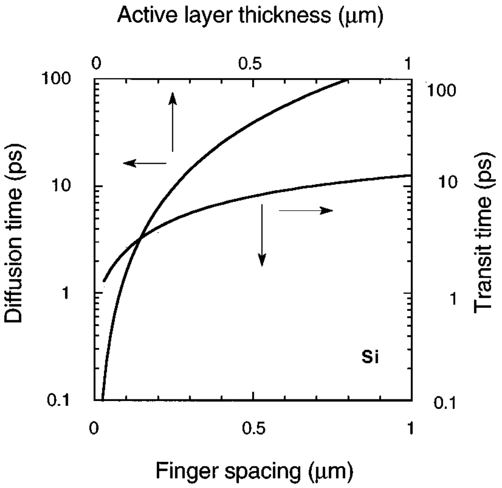

FIG. 1. Theoretical simulations of the response time in a Si MSM photodetector. When the active layer thickness of the detector is larger than 200 nm, the response is dominated by the diffusion time of the deeply generated carriers.

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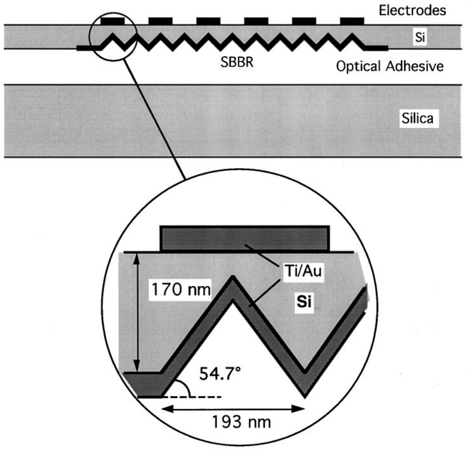

FIG. 2. Structure of the MSM photodetector on SOI with SBBR realized by coating a 20/30-nm-thick Ti/Au layer on the backside of the Si layer patterned with inverted pyramids.

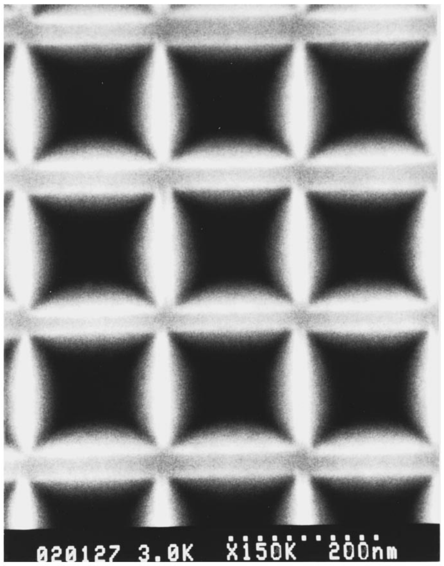

FIG. 3. SEM image of the inverted pyramids. Each pyramid has a side length of 193 nm with a slope of 54.7°.

reflector (SBBR), consisting of nanometer-scale patterned structures. When light enters into the Si layer, it will be scattered back by the SBBR. The scattered light is then reflected by either the front internal surface of the active layer through total internal reflection (TIR) or the electrodes. The successive reflections between the front internal surface and the SBBR cause light to be trapped inside the active layer. Therefore, this device has much less photon loss compared to those on SOI without SBBR. On the other hand, since the active layer thickness is comparable with the finger spacing, the carriers generated are in the depleted region. The high electric field in this region sweeps the carriers to the electrodes at their saturation velocities, resulting in a fast temporal response.

A commercial wafer-bonded SOI wafer with a 180-nm-thick (100) orientation p-type Si active layer was used as the starting substrate. A 23-nm-thick SiO_2 was first thermally grown on its surface, reducing the thickness of the Si layer to 170 nm. Square-shaped holes with 100-nm sides and 200-nm pitches were patterned into the SiO_2 layer by e-beam lithography and HF etching. The patterned SiO_2 was then used as a hard mark for patterning the Si layer through isotropic etching using a KOH solution. Since the KOH solution has an etching rate 500 times higher in the [100] direction than in [111], inverted pyramids were formed. As shown in Fig. 2 and 3, each pyramid has a side length of 193 nm with a slope of 54.7°, which is the angle between the (100) and (111) planes of the Si substrate. The total grid area is 20×26 μm^2. After removing the grown SiO_2 layer, a 20/30-nm-thick Ti/Au metal was evaporated on the surface to improve its reflectivity. The wafer was then bonded on a silica substrate using an optical adhesive (Norland Optical Adhesive 61, $n=1.56$). The Si substrate of the SOI wafer was removed by mechanical polishing and KOH etching. Finally, the exposed buried oxide (BOX) layer of the SOI substrate was etched in HF solution. Metal fingers of 15/30-nm-thick Ti/Au with spacings ranging from 100 to 600 nm were then deposited on the exposed Si surface using e-beam lithography and lift-off. The finger's width-to-spacing ratio was 1:1 with a deviation of 10%. As shown in Fig. 2, the final active layer has a maximum thickness of 170 nm and a minimum thickness of 34 nm. The average thickness is 102 nm. Since the temporal response of a MSM photodetector is determined by the slowest carrier in the substrate, we expect the speed of the photodetector to be close to that of those on plain SOI substrates with 170-nm-thick Si layers.

The transmission of the SBBR, measured before depositing the metal fingers, was found to be less than 4%. The refractive index of Si is 3.88 at a wavelength of 633 nm and 3.67 at a wavelength of 850 nm,[14] resulting in TIR angles of 14.9° and 15.8°, respectively. Therefore, at both wavelengths, most of the scattered light will approach the front internal surface of the active layer at an angle larger than the TIR angle and be completely reflected. For the light with an angle less than the TIR angle, it will be partially reflected by either the fingers or the Si-air surface. Assuming an isotropic scattering by the SBBR and counting the reflections from the fingers and the Si-air surface, 98.9%–98.7% of the light will be reflected by the front internal surface at the wavelengths of 633–850 nm. In other words, the light leakage of the front surface is less than 1.3%. Counting the additional 67% reflection on the incident light from the detector's external surface (50% by the fingers and 34% by Si substrate) and the 4% transmission loss from the SBBR, a 31% absorption by the Si layer is expected. As a comparison, we calculated the absorption of a plain 170-nm-thick Si layer on a SiO_2 substrate using the equations given in Ref. 15. The results were 8.9% and 1.4% at the wavelengths of 633 and 850 nm, respectively, which are much smaller than 31%.

The responsivities of MSM photodetectors with and without the SBBR were measured at 633 and 850 nm wavelengths, with optical powers of 8.05 and 114 μW, respectively. Figure 4 shows the photocurrents of the MSM photodetectors with a 300-nm finger spacing at 633 nm wavelength. The responsivity of the detector with the SBBR is 0.29 A/W at a bias of 2.0 V, corresponding to an external efficiency of 57%, which is 19 times larger than that of the one without the SBBR (15 mA/W). The external efficiency is larger than the 31% theoretical absorption by almost twofold,

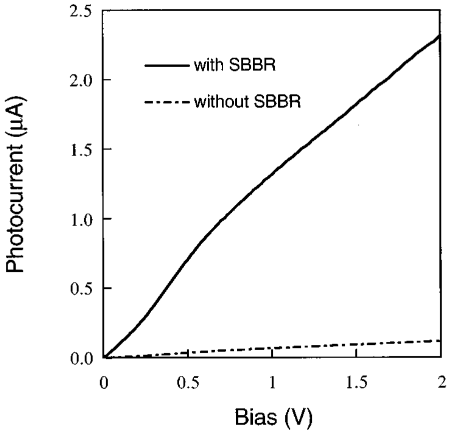

FIG. 4. Photocurrents of 300-nm finger spacing MSM photodetectors on SOI with and without the SBBR at the wavelength of 633 nm. The incident optical power is 8.05 μW.

indicating an excess 100% quantum efficiency, caused by the photoconductive gain in the detector.[3] At 850 nm wavelength (Fig. 5), the responsivity of the detector with the SBBR is 130 mA/W at a bias of 2.0 V, corresponding to an external efficiency of 19%, which is 18 times larger than that of this without the SBBR (7.3 mA/W). This external efficiency is smaller than that at 633 nm. We attribute it to the lateral light loss due to light scattered into the area far away from the electrodes inside the active layer. Since the light absorption length of Si is much larger at wavelength of 850 nm than at 633 nm, more light is lost laterally at 850 nm. Nevertheless, the responsivities of the detectors with the SBBR at both wavelengths are at least an order of magnitude larger than those without the SBBR.

The impulse response of the detector was measured using a zero-propagating-distance electrooptic (EO) sampling system[16] and a Ti-sapphire laser with a pulse width of 150 fs at 780 nm wavelength. The system has a temporal resolution of 300 fs. Figure 6 shows the impulse response of the 300-nm detector. A FWHM of 5.4 ps has been observed, corresponding to a 3-dB bandwidth of 82 GHz. The measured response is in a good agreement with the theoretical predictions shown in Fig. 1. Further increase in the detector's speed is expected if the maximum active-layer thickness is reduced below 100 nm.[9]

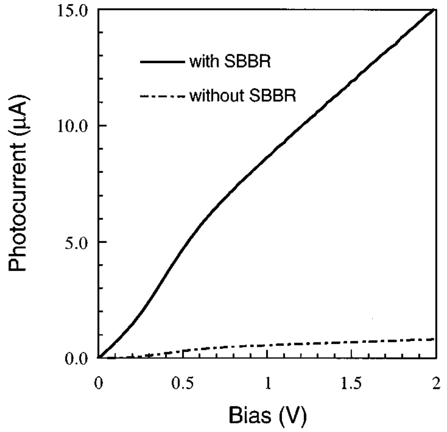

FIG. 5. Photocurrents of the same MSM photodetectors in Fig. 4 but at the wavelength of 850 nm. The incident optical power is 114 μW.

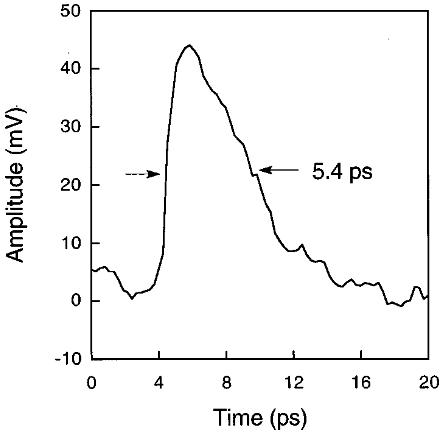

FIG. 6. Impulse response of the 300-nm MSM photodetector measured by an EO sampling system. The wavelength is 780 nm.

In summary, we have proposed and demonstrated a silicon MSM photodetector with high-efficiency and high-speed in the infrared. To achieve the high speed, a SOI substrate with 170-nm-thick Si active layer is used to eliminate the deep-carrier generation which exists in a bulk substrate; to achieve the high efficiency with such a thin active layer, a scattering reflector, consisting of nanometer-scale inverted pyramids, is buried underneath the thin Si active layer. This scattering buried backside reflector causes light trapping inside the thin Si active layer, resulting in a minimal reduction in the detector's responsivity while reducing the transit time of the photogenerated carriers. A FWHM response of 5.4 ps has been observed at the wavelength of 780 nm, corresponding to a 3-dB bandwidth of 82 GHz. At both visible and infrared wavelengths, the responsivities of the photodetectors with the buried backside reflectors are an order of magnitude larger than those without the reflectors.

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