

140-GHz metal-semiconductor-metal photodetectors on silicon-on-insulator substrate with a scaled active layer

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Metal-semiconductor-metal photodetectors with 100-nm finger spacing and width on a silicon-on-insulator substrate that has a scaled active layer were fabricated and characterized using electro-optic sampling. The unique device structure cuts off carriers generated deep inside the semiconductor substrate, resulting in a measured response time of 3.2 ps and a bandwidth of 140 GHz. Furthermore, the detector structure makes the detector's speed independent of the light penetration depth and thus the light wavelength. Good metal-semiconductor Schottky contact and low detector dark current have been achieved.

Metal-semiconductor-metal photodetectors (MSM PDs) are very attractive for many optoelectronics applications, such as optical communication, future high-speed chip-to-chip connection, and high-speed sampling. Recently, we have reported 510-GHz MSM PDs on low-temperature-grown (LT) GaAs¹ and 110 GHz on bulk Si.² However, the response time of the reported Si MSM PDs depends on the light wavelength and the fast response was achieved only at short wavelengths (~ 400 nm). At long wavelengths, such as that of GaAs lasers (~ 800 nm), the bandwidth of the detectors dropped to ~ 40 GHz. This is because that collecting the photogenerated carriers that are deep inside the semiconductor takes a long time. This wavelength dependence in response and the slow speed at long wavelength impose serious limitations to the Si detector's applications.

To solve this problem, in this letter, we report on MSM PDs on silicon-on-insulator (SOI) substrate with a scaled top Si layer. In a SOI wafer, a layer of buried oxide separates a thin top Si layer from the bulk Si substrate. By fabricating MSM PDs on thin top Si layer, the carriers generated deep inside the bulk substrate are isolated from the detector's active region by the buried oxide and therefore will not affect the detector's speed. In addition to the high speed, such detector structure has three more advantages. First, the detector speed becomes independent of light penetration depth, and therefore independent of the light wavelength (assume the light wavelength is shorter than semiconductor band-gap wavelength). Second, SOI MSM PDs have smaller device capacitance than bulk Si detector due to the smaller dielectric constant of the oxide layer, allowing a smaller RC constant and, hence, a higher possible device speed. Finally, it has demonstrated that SOI is suitable for high-speed nanoscale field effect transistor (FET) based circuits,³ therefore integration of SOI MSM PDs with the SOI high-speed circuits makes high-speed SOI optical receivers possible.

The key concept of the SOI detector scaling is to make the carrier diffusion time from the bottom of the active layer to the metal fingers comparable to the carrier transit time between the metal fingers. To do so, we plot in Fig. 1 the diffusion time as a function of the active layer thickness calculated from the diffusion equation, and the transit time versus the finger spacing calculated from a one-dimensional (1-D) Monte Carlo model.⁴ For a detector with 100-nm fin-

ger spacing, the transit time is ~ 3 ps. To make the diffusion time comparable to the transit time, we can see from Fig. 1 that the active layer thickness should be scaled to 100 nm. In this SOI structure, the thickness of the active layer can be much smaller than the light penetration depth, making the detector's speed independent of the light wavelength and achieving a fast response at long wavelengths.

The SOI detectors were fabricated on commercial SIMOX (Separation by IMplanted OXYgen) wafers. The *p*-type Si top layer of a doping concentration of 10^{15} cm⁻³ has been thinned to 100 nm through oxidation and wet etch in HF. The thickness of the buried oxide layer is 370 nm. Interdigitated electrodes with finger spacing and width of 100 nm were fabricated using electron beam lithography and a lift-off technique.⁵ The detector has an active area of $5 \mu\text{m}$ by $5 \mu\text{m}$ and a capacitance of 8 fF. Coplanar striplines with 10- μm gap and 20- μm linewidth were integrated with the detectors using photolithography for the electro-optic sampling measurements. The impedance of the transmission line is about 60Ω , so the estimated RC time constant is only 0.5 ps, and is not a limiting factor to the detector's speed.

Figure 2 shows the device dc current-voltage characteristics. The device demonstrates good current saturation, indicating a good Schottky barrier at the metal-semiconductor

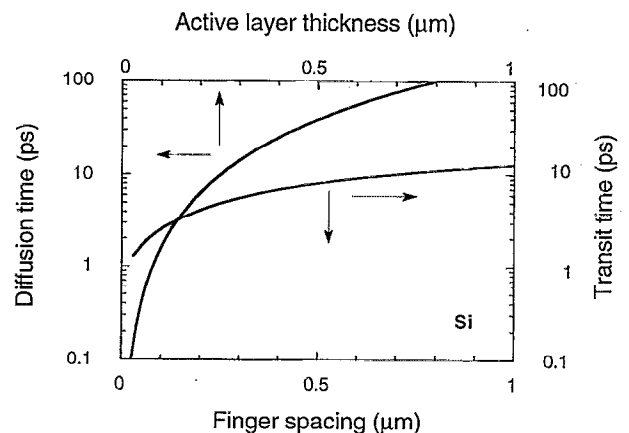


FIG. 1. The carrier diffusion time vs the active layer thickness, and the carrier transit time vs the finger spacing.

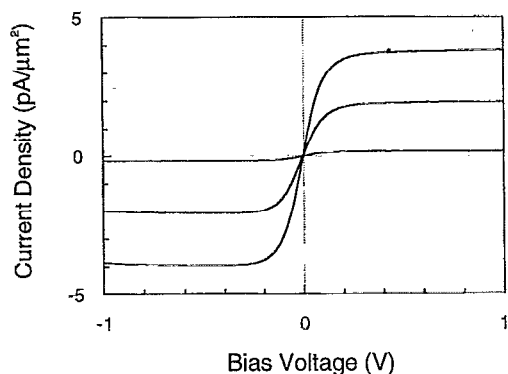


FIG. 2. Current-voltage characteristics of a SOI MSM PD at various illumination levels. The curve with the smallest current density shows the dark current-voltage characteristics.

interface. The dark current is only $0.2 \text{ pA}/\mu\text{m}^2$. From a Richardson thermionic emission equation and a Richardson constant of $30 \text{ A}/(\text{cm}^2 \text{ K}^2)$ for p -type Si substrate,⁶ we calculated the Schottky barrier height to be 0.71 V . The responsivity of the detector depends strongly on the wavelength, because the number of photogenerated carriers in the active layers depends directly on the absorption coefficient of silicon. For a top Si layer thickness of 100 nm , the responsivity is 5.7 mA/W at 780 nm and 12 mA/W at 633 nm , such a low responsivity is due to the very thin active layer that absorbs only a small portion of incident photons. Since the absorption coefficient is greater at shorter wavelength in Si, the responsivity at 633 nm is larger than at 780 nm .

The detector with 100-nm finger spacing and width was measured using an electro-optic sampling system⁷ and a mode locked $\text{Ti}:\text{Al}_2\text{O}_3$ laser. The laser has a pulse width of 150 fs and a wavelength of 780 nm . Figure 3 shows the impulse response of the detector with a full width at half-maximum (FWHM) of 3.2 ps , corresponding to a 3-dB bandwidth of 140 GHz . Unlike the impulse response of the MSM PDs in bulk Si that has a long tail due to the carriers generated deep inside the semiconductor bulk, the response of the SOI MSM PD has a very short tail of only $\sim 10 \text{ ps}$. This is attributed to the thin Si active layer in the SOI structure.

The measured 3.2-ps response time agrees fairly well with a one-dimensional Monte Carlo simulation result,⁴ indicating that the detector's response is mainly attributed to the carrier transit-time across the metal fingers, not the carrier diffusion time. To make the detector even faster, one must use a smaller finger spacing and a thinner top active layer simultaneously. Using the Monte Carlo simulation and assuming the 1D model is valid,⁴ we predict that, when the

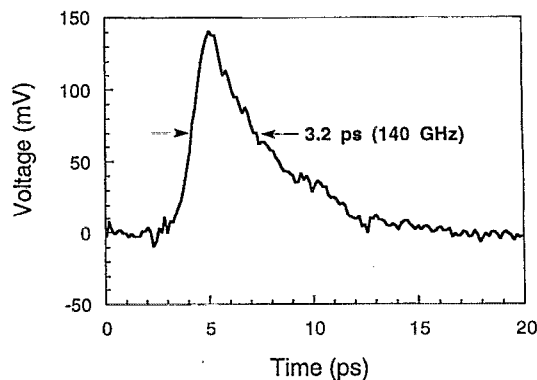


FIG. 3. Impulse response of a SOI MSM PD with a 100-nm finger spacing. The laser wavelength is 780 nm .

finger spacing is reduced to 25 nm , SOI MSM PD can have a response time as small as 1 ps and a bandwidth as high as 400 GHz . However, this requires the active Si layer thickness be reduced at the same time, making the detector's responsivity low. Therefore, the detector's high-speed performance is achieved at the expenses of low responsivity. A tradeoff must be made according to requirement of a particular application. To improve the responsivity without lowering the speed, a quarter-wave stack reflector underneath the active layer and an antireflection coating on the top can be employed. The quarter-wave stack may be achieved using alternative Si/SiGe layers.

In summary, we have fabricated SOI MSM PDs with a scaled active layer and nanometer scale fingers. The detector has a response time of 3.2 ps and a bandwidth of 140 GHz . Good Schottky contacts, and therefore low dark current, have been achieved. The responsivity of the devices is low due to the thin active layer and depends on wavelength.

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