

32 GHz metal-semiconductor-metal photodetectors on crystalline silicon

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Interdigitated metal-semiconductor-metal (MSM) photodetectors with $1.2\ \mu\text{m}$ finger spacing and $0.8\ \mu\text{m}$ finger width were fabricated on crystalline Si substrate. The devices are transit time limited, exhibiting a measured full width at half maximum response time of 14 ps and a 3-dB bandwidth of 32 GHz. Monte Carlo simulations of Si MSM photodetector response time and bandwidth agree with experiments and predict that if the finger spacing of the Si MSM photodetectors is reduced to 25 nm, the response time can decrease to ~ 1 ps and the bandwidth can increase to 440 GHz.

Metal-semiconductor-metal photodetectors (MSM PDs) have received considerable attention as candidates for optical communication system and high speed chip-to-chip connection because of high sensitivity-bandwidth product and compatibility with large scale planar integrated circuit technology. Previously, most work on MSM PDs was focused on GaAs¹⁻³ and InGaAs,^{4,5} and relatively little work has been reported on crystalline Si,^{6,7} which is the backbone material for today's integrated circuits. Recently, a MSM PD with a $4\ \mu\text{m}$ single gap on crystalline Si has an intrinsic 3-dB bandwidth of 22 GHz characterized using a continuous-wave laser heterodyne system.⁷ In this letter, we report interdigitated MSM PDs of $1.2\ \mu\text{m}$ finger spacing, fabricated on crystalline Si using electron beam lithography, with a measured full width at half maximum (FWHM) impulse response of 14 ps and a bandwidth of 32 GHz. To our knowledge, the detector is the fastest MSM PD on crystalline Si reported so far. We also present a Monte Carlo study of the detector response time and the detector scaling for high-speed operation.

The MSM PDs were fabricated on a *p*-type Si wafer with a doping concentration of $\sim 8 \times 10^{14}\ \text{cm}^{-3}$. Interdigitated electrodes of $1.2\ \mu\text{m}$ spacing and $0.8\ \mu\text{m}$ width were defined using electron beam lithography and a liftoff process. The interdigitated patterns were exposed in the double layers of polymethylmethacrylate (PMMA) coated on the Si surface using an electron beam lithography system at a beam energy of 35 keV. After development, metals (15 nm Ti and 35 nm Au) were evaporated onto the samples and were lifted off in acetone. The active area of the detector is $20\ \mu\text{m} \times 20\ \mu\text{m}$ (Fig. 1). The detector was connected with two $150\ \mu\text{m} \times 150\ \mu\text{m}$ metal pads separated by $100\ \mu\text{m}$ for measurement.

The parasitic capacitance of the detector and its contact pads were measured at 1 MHz using a Hewlett-Packard 4280 A capacitance meter. The capacitance of the contact pads was 30 fF. The detector capacitance was 10 fF or 0.05 fF per unit micron finger length, deduced by subtracting the contact pads' capacitance from the total device capacitance, and agreeing with the theoretical value.⁸

In the high-speed impulse measurement, the detectors were excited by a colliding-pulse mode-locked dye laser with a pulse duration of ~ 250 fs and a wavelength of 620

nm, and the electrical signal from the detector was picked up by a probe station with a 40 GHz bandwidth and was measured by a 50 GHz sampling oscilloscope. The FWHM of the measuring system was found to be 12 ps. The system impedance is $50\ \Omega$, and the RC time constant of the detector is 2 ps, which is not an important factor to the system response.

We measured the detector impulse response as a function of bias for a beam energy of 0.2 pJ per pulse. Figure 2 shows that the FWHM decreases as the bias increases, indicating that the detector response is transit time limited. The saturation of the response time is due to the saturation velocity of the carriers. The impulse response of the detector at a bias of 12.5 V is shown in Fig. 3; the response has a FWHM of 18.7 ps. Because the measuring system has a FWHM of 12 ps, a simple Gaussian deconvolution response time yields an intrinsic device FWHM of 14.3 ps. Since the detector response has a Gaussian distribution, the corresponding 3-dB bandwidth is, calculated from $0.441/(\text{FWHM})$, 32 GHz. The 14-ps FWHM is not unexpected, since the average transit time for electrons to cross a $1.2\ \mu\text{m}$ distance with a saturation velocity of 1×10^7 cm/s is 12 ps.

Figure 3 shows that the tail of the detector's impulse response is 144 ps. Since the penetration depth of 620 nm light in Si is $\sim 3\ \mu\text{m}$ —much deeper than the region where

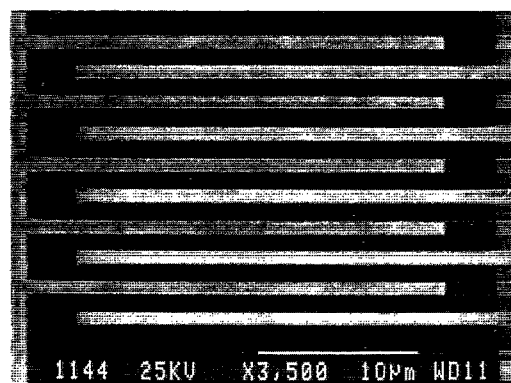


FIG. 1. Scanning electron micrograph of a Si MSM PD. The finger spacing is $1.2\ \mu\text{m}$ and the finger width is $0.8\ \mu\text{m}$.

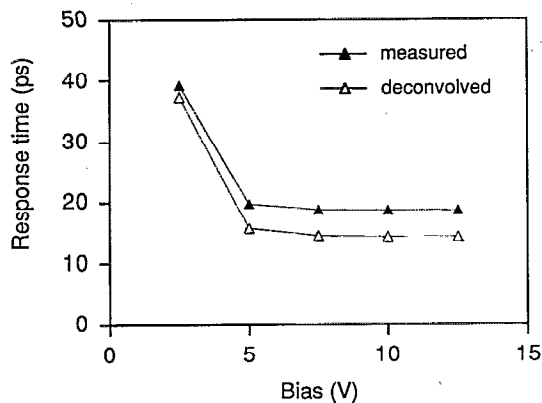


FIG. 2. The FWHM impulse response of the MSM PD vs the bias. One curve is the measured responses and the other is the deconvolved.

the electric field lines concentrate—and the carrier lifetime in crystalline Si is over 100 ns, one might suspect that significant portion of photoexcited carriers are in the low field region and that the tail in the detector response might be due to the diffusion of carriers generated deep inside semiconductor. However, measurements showed that for MSM PDs with different finger spacing fabricated on the same Si wafer, the tail of the response had different decay time constant.⁹ This is inconsistent with the carrier diffusion model, which requires that the diffusion of carriers depends only on the light penetration depth, not the finger spacing, and that the tail in the response of detectors with different finger spacing should have a similar decay time constant. The details of effects of photogenerated carriers deep inside semiconductor to the impulse response is still under investigation.

We used a one-dimensional Monte Carlo method to simulate the impulse response of the MSM PDs. Figure 4 shows the simulation of the impulse response of the MSM PD with 1.2 μm finger spacing. By separating the electron current from hole current, it shows that the long tail in the

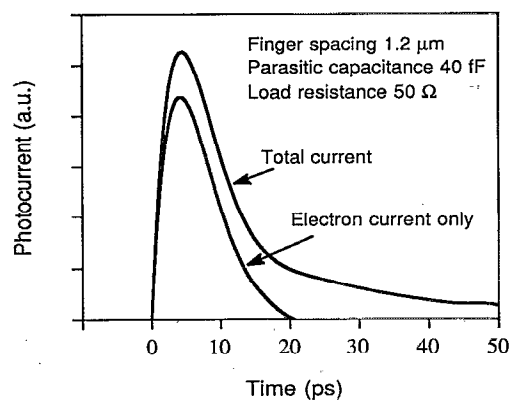


FIG. 4. A Monte Carlo simulation of the impulse response of MSM PD with 1.2 μm finger spacing. The total detector capacitance is measured to be 40 fF. The load resistance is 50 Ω .

simulated impulse response is from slow-moving holes. The diffusion of carriers generated deep inside semiconductor is not included in the 1-D model.

Figure 5 shows the Monte Carlo simulation of the FWHM of the intrinsic response time as a function of the finger spacing. Further reduction of the intrinsic response time can be achieved by reducing the finger spacing in Si MSM PDs, which is possible by using electron beam lithography, x-ray lithography, or focused ion beam lithography. Recently, we have achieved interdigitated lines with 25-nm spacing and width on bulk GaAs.³ The same fabrication techniques are also applicable to Si MSM PDs. For a Si MSM PD with 25-nm finger spacing, the FWHM intrinsic response time can be as small as ~ 1 ps and the 3-dB bandwidth can reach 440 GHz.

To achieve fast external response time, however, proper scaling is required. As finger spacing and therefore the transit time become smaller, the effects of two parasitic elements must be considered: the parasitic capacitance and the metal finger resistance. Namely, RC time constant can be a limitation to the device response time. For a given detector area, to reduce the capacitance, the ratio of the finger width to the finger pitch (i.e., the sum of the finger width and spacing) should be reduced.⁸ However, the re-

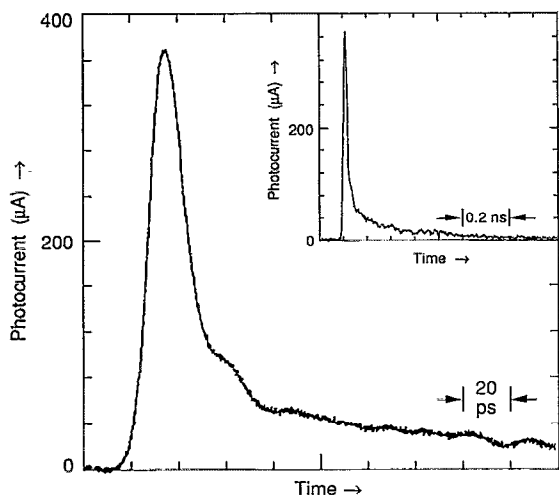


FIG. 3. A time-response trace of a Si MSM PD identical to that of Fig. 1, illuminated with a 250 fs CPM dye laser. Inset: the device response over a longer time scale.

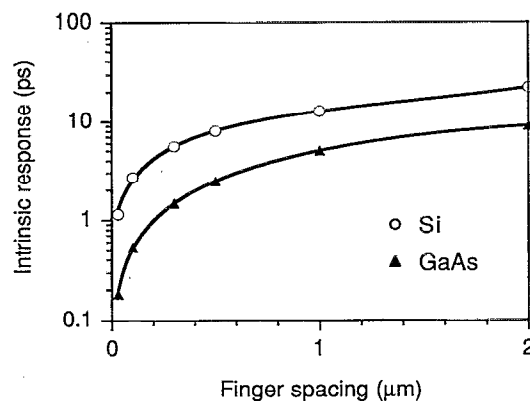


FIG. 5. A Monte Carlo simulation of the intrinsic response time vs finger spacing, on Si and GaAs MSM PDs. The average electric field in the semiconductors is 50 kV/cm.

duction of finger width causes an increase in the series resistance. As the finger width approaches the submicrometer scale, the thin metal line resistance is shown to be much greater (by about a factor of 4–8) than that calculated from bulk resistivity.⁸ To reduce series resistance, a thicker metal layer or shorter length per finger is desired.

In conclusion, we have fabricated interdigitated MSM PDs on crystalline Si. Direct high-speed measurement showed that the FWHM impulse response is 14 ps for a detector with 1.2 μm spacing and 0.8 μm finger width, which is the fastest MSM PD on crystalline Si reported to date. A Monte Carlo simulation shows that 25-nm Si MSM PDs may have an intrinsic response time of 1 ps and 3-dB bandwidth of 440 GHz, which is very promising for applications in high-speed optical communication. Proper scaling of parameters of picosecond Si MSM PDs was discussed.

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