A 75 GHz silicon metal-semiconductor-metal Schottky photodiode

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The ultrafast characteristics of crystalline-silicon metal-semiconductor-metal (MSM) photodiodes with 300 nm finger width and spacing were measured with a subpicosecond electro-optic sampling system. Electrical responses with full width at half maximum as short as 5.5 and 11 ps, at corresponding 3 dB bandwidths of 75 and 38 GHz, were generated by violet and red photons, respectively. The difference is attributed to the photon penetration depth which is much larger than the diode finger spacing at red, but smaller at violet. Light-intensity dependence was also examined at different wavelengths, indicating a linear relation and a higher sensitivity in the violet. These results not only demonstrated the fastest silicon photodetector reported to date, but also pinpointed the dominant speed-limiting factor of silicon MSM photodiodes. A configuration is suggested to improve the speed of these detectors at long wavelengths.

Metal-semiconductor-metal (MSM) photodiodes are a family of fast, high-sensitivity detectors. Their simple planar structures enable easy fabrication in a process compatible with planar circuit technology and are hence attractive for use in integrated optoelectronic-electronic systems. In the past, most attention was given to MSM diodes made on III-V substrates.[1–5] For example, we have reported on a range of MSM detectors made on low-temperature MBE-grown and semi-insulating GaAs with finger period as short as 100 nm.[1] These detectors had speed, measured by the full width at half maximum (FWHM) of the response transient, as fast as 0.87 ps. A comparison of our experimental results to Monte Carlo simulations demonstrated that the speed of these detectors was limited by their intrinsic *RC* time constant. Furthermore, since the underlying physical principle of ballistic transport is applicable to all semiconductors, it was inferred that comparable performance should also be achievable in silicon. Monte Carlo simulations predicted[6] a response speed as short as 6 ps FWHM for silicon MSM diodes with finger width and spacing of 300 nm.

Preliminary results on 1.2 μm and 300 nm silicon diodes,[7,8] measured with colliding pulse mode locked dye lasers (wavelength = 620 nm), however, indicated much slower response (14 and 11 ps, respectively) than the III-V compound detectors. In addition, these devices had a long "tail" response—a residual electron drift component past the main peak—as long as 1.4 ns for the 1.2 μm diodes.[7] The latter is a particularly undesirable feature for practical applications, since photoconductive current is cumulative—the device has to fully recover to its original, nonconductive state before the next optical pulse can be detected—thus limiting its use to less than 1 Gb/s. It was suggested[8] that a probable source of the slow response and the long tail is due to deep-carrier generation because of the long penetration depth of photons at wavelengths used in these experiments.

In this letter, we demonstrate that this is indeed the case. We report on the fastest photodetectors made with essentially undoped crystalline silicon, and show that by decreasing the wavelength of the excitation photons, hence reducing the light penetration depth, these diodes can have a speed close to the Monte Carlo predictions. Furthermore, at this photon wavelength, the slower drift-current component is completely eliminated. By pinpointing the speed-limiting factor of these devices, we are able to suggest a configuration for improving the temporal response of the diodes in a wide range of wavelengths.

Our MSM diodes were fabricated on unintentionally doped crystalline silicon ($p < 10^{15}$ cm^{-3} and carrier recombination time > 100 ns) using electron beam lithography. A 50-nm-thick Ti/Au metallization was chosen for the interdigitated fingers to ensure a Schottky barrier at the metal-semiconductor interface. Ten fingers with 300 nm width and separation formed a diode active area of 5×5 μm^2. The diodes were positioned in parallel to a 65 Ω coplanar transmission line, as shown in Fig. 1.

The response of the devices was tested using a subpicosecond electro-optic sampling system similar to that described in Refs. 9 and 10. Typical bias voltage across the diode was 3 V. A femtosecond Ti:Al_2O_3 laser provided tunable pulses in the red to near-infrared (700–1000 nm) range at a 76 MHz repetition rate and was used for both excitation and probing. A movable $LiTaO_3$ electro-optic crystal was positioned above the diode area (see Fig. 1) as the detector for the electrical transient. The excitation beam was focused down to the diode through the $LiTaO_3$ crystal, and the electrical signal was probed by the sampling beam guided through the electro-optic crystal in a total internal-reflection mode. This configuration allows the diode response to be measured directly with no propagation distortion.[10] At the fundamental wavelength range of the Ti:Al_2O_3 laser, the carrier penetration depth is > 5 μm, much larger than the finger spacing and, as a result, the photogenerated carriers are expected to penetrate deep into the substrate. To test the effect of the deep photoge-

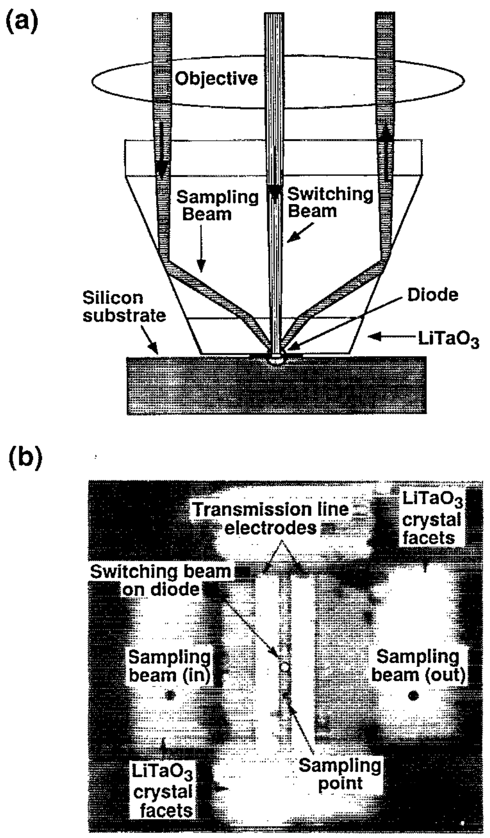

FIG. 1. (a) A schematic of the sampling geometry employed to measure the electrical response of the MSM Si photodiodes. (b) A top view of the 5×5 μm^2 MSM photodiode mounted in parallel with a 65 Ω coplanar strip. This picture is taken through the $LiTaO_3$ crystal. The excitation and sampling beam positions are indicated.

nerated carriers, the excitation beam was frequency-doubled to the violet region where the penetration depth is comparable to the finger separation. (We note that our experiments also represent the first time that a tunable, as well as frequency-doubled, electro-optic sampling system is demonstrated.)

Figure 2 (solid line) shows the fastest temporal response of the photodiode illuminated with a 0.35 pJ frequency-doubled optical pulse at a wavelength of 465 nm. The resulting waveform had a 55 mV peak amplitude and a 5.5 ps FWHM, corresponding to a quantum efficiency of 13%. The pulse shape in Fig. 2 is strongly asymmetric: the subpicosecond rise time is limited by the diode *RC* time constant and the optical pulse width; the fall time, determined by carrier transit across the fingers, has a longer duration which in turn determines the overall speed of the device. Absent from the transient is the long drift-current tail previously seen.[7,8] In fact, the zero-current state of the device is fully restored within 20 ps after the optical pulse is launched. Similar response was also measured at 380 and 400 nm.

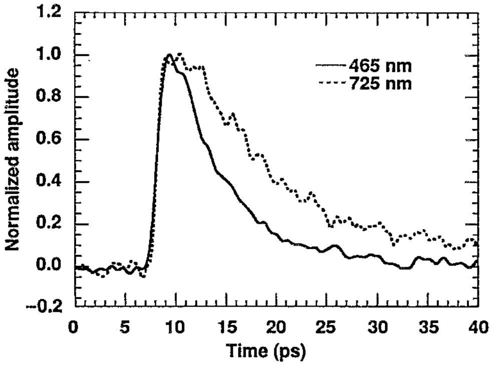

FIG. 2. Electrical pulses generated by illumination of 465 nm photons (solid line) and 725 nm photons (dotted line) on a silicon MSM photodiode. The finger spacing and width of the diode are both 300 nm.

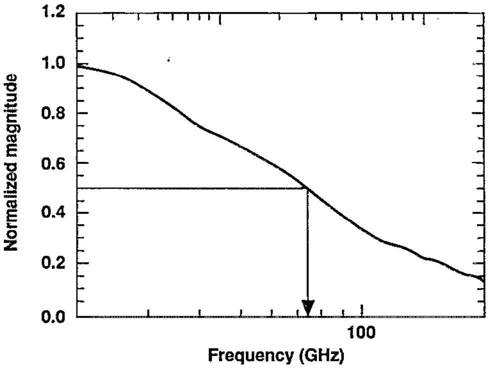

FIG. 3. Normalized spectral content of the diode response to 465 nm excitation (from Fig. 2, solid line).

The normalized spectrum of this pulse is shown in Fig. 3, with a 3 dB cutoff directly determined to be 75 GHz. By keeping the device *RC* time constant and the photon penetration depth both at minimum, the speed and bandwidth characteristics are in close agreement with Monte Carlo simulations.[6]

When the wavelength of the excitation pulses was switched to red (725 nm), the temporal response of the device degraded significantly (Fig. 2, dashed line). The rise time is unchanged, but the fall time is now increased to 11 ps, with the 3 dB bandwidth reduced to 38 GHz. A drift tail is visible, and the device does not return to the nonconductive state until 40–50 ps past the onset of the optical pulse (not fully shown in Fig. 2). Similar response was also measured at wavelengths of 750, 760, and 795 nm.

Since the major difference between the responses of silicon to violet and to red excitations is the photon penetration depth, it appears reasonable to attribute the latter, slower response to deep carriers generated by the photons. These carriers are well separated from the electrodes and would produce additional current as they drift upward toward the electrodes. It should, however, be noted that our observed "tail" in the device transient is more than 30-fold shorter than that seen for the 1.2 μm diodes,[7] although the finger spacing is only four times shorter, indicating perhaps a much reduced excessive photoconductive current in the smaller diode. It would be of interest to examine this effect using two-dimensional Monte Carlo simulations and to compare them with the experimental results.

The pulse amplitude had a linear dependence on the

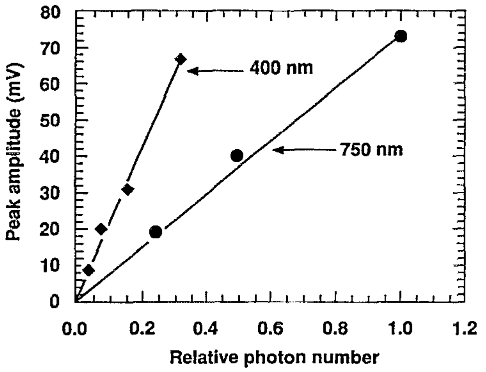

FIG. 4. Dependence of the pulse amplitude on the number of incident photons at 400 and 750 nm.

number of incident photons, as seen in Fig. 4. There are two distinct slopes for the violet and the red, which is a further indication that the deep carriers have a significant effect on the diode response: for red excitation, a large portion of the carriers are generated deep in the substrate and do not reach the electrodes in the first few picoseconds to contribute to the main peak.

Our results point to an interesting way for improving the device speed at longer wavelengths: The MSM diodes can be fabricated on a layer of silicon, perhaps 0.2–0.5 μm thick, backed with a buried dielectric underlayer to limit deep-carrier generation. The diode would then have speed limited by the silicon thickness. The only drawback is that the photon conversion efficiency would be reduced when the penetration depth exceeds the silicon thickness, since a portion of the photons would not be absorbed. This can be partially remedied by choosing a large index of refraction for the dielectric to reflect the light.

In conclusion, we have demonstrated ultrafast silicon MSM photodetectors that had a 3 dB bandwidth of 75 GHz. The planar processing and lithographic requirements of these detectors are directly compatible with modern silicon integrated circuits, making these diodes important for optoelectronic applications. Detailed dependencies of the diode response on light wavelength and intensity have been measured, and we found these devices to operate particularly well in the violet where deep-carrier generation is unimportant. Based on our findings, a configuration has been suggested to improve the speed response of the MSM diodes at longer wavelengths where the penetration depths exceed the finger spacings.

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