

Internal emission metal-semiconductor-metal photodetectors on Si and GaAs for 1.3 μm detection

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Si and GaAs metal-semiconductor-metal photodetectors with finger spacing as small as 0.25 μm are studied for 1.3 μm wavelength operation. It was found that the detectors have an external quantum efficiency as high as 0.5% for 1.3 μm light and a low dark current at room temperature. Increasing the Schottky barrier height reduces the responsivity of the detectors, but reduces the dark current more significantly and increases the responsivity-to-dark-current ratio. The condition for maximum signal-to-noise ratio was derived. Finally, the dependence of the detector's responsivity on the finger spacing was studied. Both the field-enhanced injection and charge-carrier screening were found to significantly affect the detector's responsivity. © 1995 American Institute of Physics.

Recently, metal-semiconductor-metal photodetectors (MSM PDs) have drawn much interest because of their potential for high-speed optical detection, large-scale integration and applications in future high-speed optical communication systems. We have reported high-speed MSM PDs with bandwidths over 500 GHz on GaAs¹ and over 100 GHz on Si.² Traditionally, the operation of MSM PDs is based on interband transition with a cutoff wavelength, $\sim 0.8 \mu\text{m}$ for GaAs and $\sim 1.1 \mu\text{m}$ for Si, which are not in the 1.3–1.55 μm wavelength range needed for optical fiber transmission. MSM PDs based on the internal emission over the metal-semiconductor Schottky barrier may offer a solution to this problem. Although internal emission Schottky barrier detectors have been widely used in infrared imaging systems,³ little work has been reported for internal emission MSM PDs.^{4–6} In this letter, we report on infrared internal emission MSM PDs in Si and GaAs operated at room temperature. Both responsivity and dark current at room temperature are investigated for detectors with different Schottky barrier heights. Measurements show an increase in responsivity when reducing the spacing between two finger electrodes. However, when optical power is high, the detectors with a very small finger spacing may have less responsivity due to carrier screening.

A traditional MSM PD gives an electrical signal when the incident photon energy is greater than the semiconductor band gap. In an internal emission detector, however, the photon energy is smaller than the semiconductor band gap, but greater than the Schottky barrier height at the semiconductor-metal interface. Therefore, for a Schottky barrier height of about 0.7 eV, the detectors can detect photons with wavelength as long as 1.7 μm . This wide wavelength range for detection is ideal for applications in future high-speed 1.3 or 1.55 μm optical fiber communication systems. Compared to the metal-semiconductor Schottky barrier detectors used in infrared imaging systems where the Schottky barrier height is typically smaller than 0.4 eV, the Schottky barrier heights in the MSM PDs are much larger; leading to a much smaller dark current, therefore, making the detectors suitable for

room-temperature operation. Certainly, the penalty is a lower responsivity.

Interdigitated metal electrodes are fabricated on double-side polished *n*- and *p*-type Si (carrier concentration $\sim 10^{15} \text{ cm}^{-3}$) and undoped semi-insulating GaAs using photolithography or electron-beam lithography. The finger spacing and width range from 2 to 0.25 μm . 20 nm thick Ti and 200 nm Au were used to form Schottky contact on GaAs and *p*-type Si, and 20 nm Pt and 200 nm Au on *n*-type Si. A 1.3 μm wavelength semiconductor laser beam is focused from the backside of the wafer onto detector active area.

The dark current density of the Si MSM PDs with an electrode size of $10^4 \mu\text{m}^2$ is about 10^{-2} A/cm^2 at 0.5 V bias. The incident light is chopped at about 1 kHz and the photocurrent is measured by a lock-in amplifier. Figure 1 shows room-temperature photocurrent-voltage characteristics of a detector fabricated on *p*-doped Si with 1.2 μm finger spacing and 1.3 μm finger width. The photocurrent initially increases with biasing voltage, which is due to the finite carrier lifetime and only part of the photogenerated carriers can be collected at the other electrode. The photocurrent then reaches saturation, which indicates that all photogenerated carriers are collected at the electrode.⁵ The external quantum efficiency at low illumination level is 0.5%. Because only part of the light is incident on the metal fingers, the external

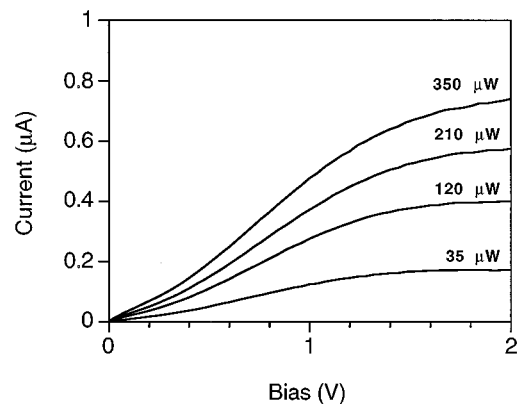


FIG. 1. Current-voltage characteristics of a Si MSM infrared detector at different illumination levels. The laser wavelength is 1.3 μm .

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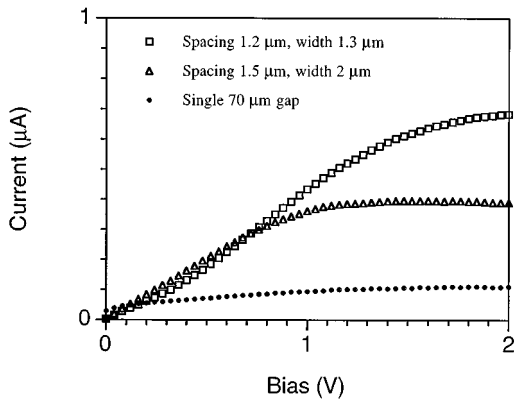


FIG. 2. Photocurrent vs bias voltage of three Si detectors with different electrode sizes.

quantum efficiency can be improved by increase the ratio of finger width to finger spacing. Compared to the Schottky barrier detectors used in the infrared imaging systems, the quantum efficiency of these MSM PDs is lower due to the relatively high Schottky barrier. The quantum efficiency of the detector can be expressed by a Fowler equation:³

$$Y \propto (h\nu - \Psi_B)^2 / h\nu, \quad (1)$$

where $h\nu$ is the photon energy and Ψ_B is the Schottky barrier height. The quantum efficiency of the detectors can be improved by using a different metal configuration to achieve a smaller Schottky barrier height. However, the dark current of the detector due to the thermionic emission is

$$I_d \propto e^{-\Psi_B/kT}, \quad (2)$$

where k is the Boltzmann constant and T the temperature. The dark current I_d increases exponentially when decreasing the Schottky barrier. A simple mathematical derivation can prove that at a given temperature and photon wavelength, Y/I_d is maximum when $\Psi_B = h\nu - 2kT$, giving the maximum signal-to-noise ratio. Since the Ψ_B in Si and GaAs is less than $h\nu - 2kT$ for 1.3–1.55 μm range, a larger Schottky barrier will lead to a greater ratio of the photocurrent to dark current under the same bias and optical power. Therefore, a larger barrier height leads to a larger detector dynamic range, assuming the current is not too small to be amplified.

The responsivity is also a function of finger spacing and finger width, as shown in Fig. 2. In the detector with 1.2 μm finger spacing and 1.3 μm finger width, 26% of the total area is covered by the forward biased fingers; while in the detector with 1.5 μm finger spacing and 2 μm finger width, 29% is covered by the forward biased fingers. One would predict that latter detector will have a greater responsivity, since more light is shining on the forward biased fingers where the carrier injection from metal occurs. However, the 1.2 μm finger spacing detector shows a greater responsivity as in Fig. 2. This can be explained by the fact that in the detector with a smaller finger spacing, the applied electric field at the metal-semiconductor interface is higher and therefore the emission of the carriers is enhanced by the larger electric field.

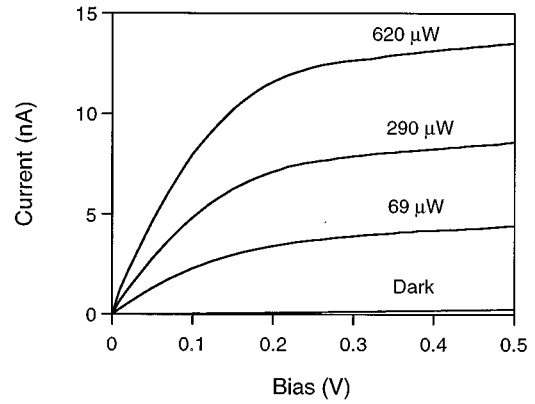


FIG. 3. Current-voltage characteristics of a GaAs MSM PD with 0.5 μm finger spacing and width.

A detector that has only two pads 70 μm apart fabricated on p -Si was also tested (Fig. 2). We found that for a given bias, when the infrared light is focused on the forward biased contact pad, the photocurrent is much greater than that when the light is focused on the reverse biased contact pad. This indicates that hole injection from the metal electrode into p -type semiconductor is the dominant process in creating photocurrent. For devices fabricated on n -Si, the opposite situation is found true, indicating that the electron injection from the metal is the dominant process. Furthermore, the photocurrent becomes nearly zero when the light spot is focused on semiconductor surface between the two pads, which demonstrates again, that the carrier injection is due to internal emission at the metal-semiconductor interface instead of interband transition.

The current-voltage characteristics of GaAs MSM detectors were directly measured using a Hewlett-Packard 4145 parameter analyzer, as shown in Fig. 3. Since the room-temperature dark current of GaAs MSM PDs is much smaller (<2 nA) than that of Si detectors, the lock-in amplifier was not used. The responsivity of GaAs detectors is smaller than that of Si detectors, due to a greater Schottky barrier height. The dependence of the responsivity on the finger spacing of the GaAs detectors was shown in Fig. 4. At low optical power, the responsivity increases as the finger spacing de-

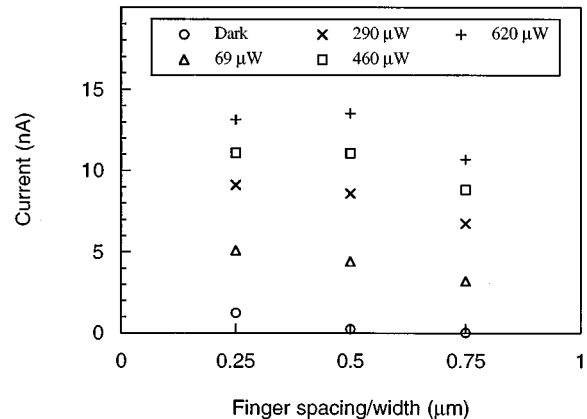


FIG. 4. Photo and dark current of GaAs detectors with different finger spacing and width at different optical power levels. The bias is 0.5 V.

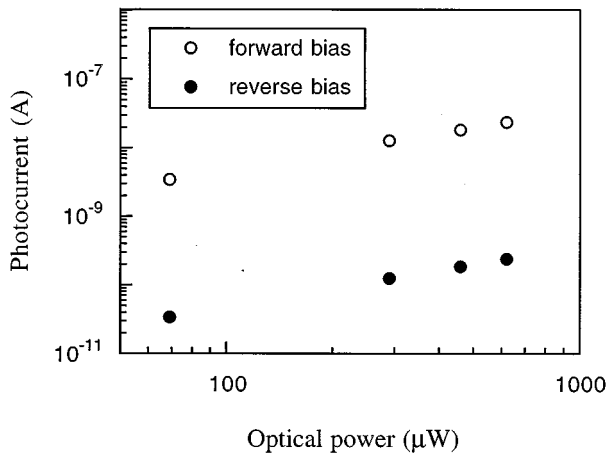


FIG. 5. Photocurrents under forward and reverse biases for a GaAs detector with a 70 μm gap.

creases, just as observed in larger Si detectors. At higher optical power, however, photocurrent will not change or even decrease as the finger spacing is decreased. This is because, at high optical power, the carriers near the metal-semiconductor interface would screen the electric field and therefore reduce the further injection of the carriers.

Finally, we tested GaAs detectors with only two metal pads by focusing the laser beam only onto one pad. We found that the photocurrent is much greater when light is shining on the forward-biased pad. This indicates that the wafer is unintentionally p -doped. Moreover, from the ratio of the photocurrents under different bias, we can calculate the

difference between the barrier heights for electrons and holes. Figure 5 shows the photocurrents of a detector under forward and reverse biases. We can see that the ratio of the two photocurrents is a constant at different illumination levels and the barrier height for holes is smaller than that for electrons.

In summary, we investigated the room-temperature performance of Si and GaAs MSM PDs for 1.3 μm wavelength operation. The detectors show reasonable infrared responsivity and low dark current, and have potential for high-speed detection at 1.3–1.55 μm wavelength. Using different semiconductor and metal configurations, different Schottky barrier heights can be achieved and the dark current and responsivity can be changed. Furthermore, reducing the finger spacing and width will also change the detector's responsivity due to field-enhanced injection and charge-carrier screening.

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