

Tera-hertz GaAs metal-semiconductor-metal photodetectors with 25 nm finger spacing and finger width

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We have fabricated metal-semiconductor-metal (MSM) photodetectors with the smallest finger spacing and finger width of 25 nm on molecular beam epitaxy grown GaAs. Direct current measurement shows that they have low dark current and high sensitivity. Monte Carlo simulations demonstrate that for a MSM photodetector with 25 nm finger spacing and width, the full width at half maximum impulse response is as short as 0.25 ps and the 3 dB bandwidth is 0.4 THz. They also show that by eliminating holes, the bandwidth can be over 1.8 THz. Furthermore, the detector capacitance was calculated, indicating that by reducing the ratio of finger width to finger spacing the detector capacitance can be decreased.

Metal-semiconductor-metal (MSM) photodetectors are very attractive for optical fiber communication systems and high-speed chip-to-chip connections.¹ The operation of a MSM photodetector can be classified into two groups according to whether its intrinsic speed is limited by recombination time or transit time. In the first group, a large number of recombination centers have to be introduced into the semiconductor to shorten carrier recombination time for high-speed operation at the expense of low sensitivity and less compatibility with field effect transistor (FET) integrated circuits fabrication. In the latter group, small finger spacing is utilized to decrease the transit time and increase the device speed; therefore, the photodetector can be built on high-quality semiconductor crystals.^{2,3} For ultrahigh-speed applications, it is very desirable to make both the spacing and the width of the interdigitated metal fingers of a transit-time-limited MSM photodetector small. The smaller the spacing, the shorter the intrinsic response time of the MSM photodetector, the smaller the finger width, the less the detector capacitance and the shorter the external response time. Furthermore, for the recombination-time-limited photodetectors, smaller finger spacing can increase the sensitivity.

Previously, the fastest transit-time-limited GaAs MSM photodetector, fabricated by Van Zeghbroeck *et al.*,² had a finger spacing of 0.5 μm and a finger width of 0.75 μm , a full width at half-maximum (FWHM) of 4.8 ps, and a bandwidth of 105 GHz. In this letter, we report fabrication of GaAs MSM photodetectors with finger spacing and finger width of 25 nm, which are, to our knowledge, the smallest ever reported. The dc characteristics show that the devices have a low dark current (< 40 nA) and a high sensitivity (0.2 A/W). Monte Carlo simulations of the MSM photodetectors indicate a subpicosecond response time and a tera-hertz bandwidth.

The MSM photodetectors were fabricated on a 0.4 μm thick undoped GaAs layer grown, using molecular beam epitaxy (MBE), on a semi-insulating GaAs substrate with an AlGaAs/GaAs superlattice in between. The superlattice is for preventing carriers generated in the substrate from entering the undoped active layer. The metal (Ti/Au) Schottky barrier contacts were fabricated on GaAs by

using electron beam lithography and a liftoff technique. For finger spacing and width greater than 100 nm, two layers of polymethylmethacrylate (PMMA) were spun on the GaAs layer for achieving a good undercut profile suitable for the liftoff. For finger spacing and width less than 100 nm, a single layer PMMA was used. Interdigitated line patterns were exposed in the resists using a high-resolution electron beam lithography system at a beam energy of 35 keV, and developed in cellosolve:methanol (3:7) developer.⁴ Metals (Ti/Au) were then evaporated onto the samples and were lifted-off in acetone. Figure 1 shows scanning electron micrographs of MSM photodetectors with different finger structures, and the smallest finger spacing and width are 25 nm.

The dc characteristics of a GaAs MSM photodetector are shown in Fig. 2. The dark current of the photodetectors is typically 40 nA at 0.5 V bias for area of 14.5 $\mu\text{m} \times 15$ μm . The sensitivity of the devices is about 0.2 A/W at the wavelength of 632.8 nm. The current-voltage characteristics do not show perfect saturation because of the surface recombination centers.

A Monte Carlo simulation program has been developed for calculating the carrier transit time. In the simulation, electric field is assumed to be one-dimensional and uniform in the semiconductor. The one-dimensional (1D) model is a good approximation since the electric field lines are mostly localized near the semiconductor interface.⁵ Recently, femtosecond testing of nanoscale MSM photodetectors on bulk semiconductors showed that the carriers generated in the bulk of a semiconductor are insignificant to the FWHM of impulse response of the detectors, and that the 1D simulation is valid even when the finger spacing is much smaller than the thickness of absorption length.⁶

Figure 3 shows the Monte Carlo simulation of the intrinsic current of a MSM photodetector with 25 nm spacing and width, and the external current after introducing the capacitance of the detector and the load resistance. It indicates that for a 25-nm-finger-spacing MSM photodetector, the FWHM of intrinsic response is 0.16 ps, and the FWHM external response is 0.25 ps. By separating the electrons from holes, we found that the current peak is due to the electrons and the long tail is due to holes which

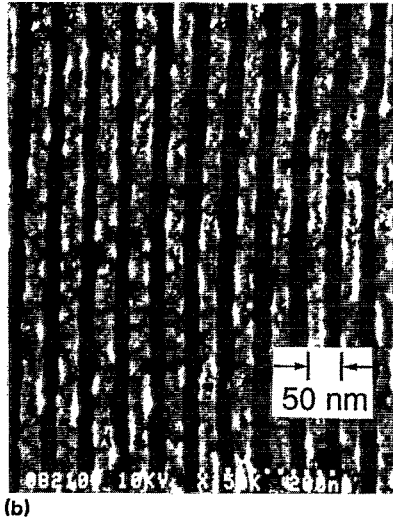
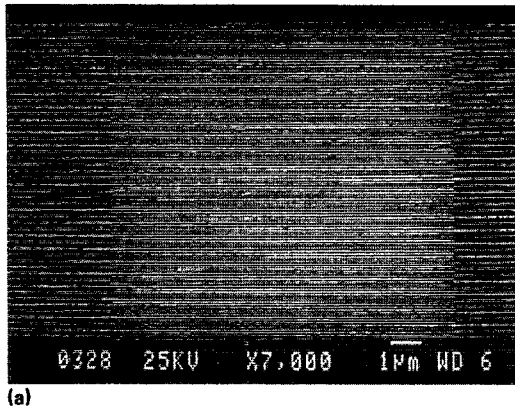


FIG. 1. Scanning electron micrographs of GaAs MSM photodetectors of (a) 50 nm finger spacing and width, and (b) 25 nm finger spacing and width.

move much slower than the electrons. Therefore, one should try to reduce or eliminate the hole current for high-speed applications. Fourier transforms of the external responses with and without hole current, a 3-dB bandwidth of the detector is 400 GHz; when the hole current is eliminated, 3-dB bandwidth is over 1.8 THz. In simulating the external response time, the load resistance is assumed to be

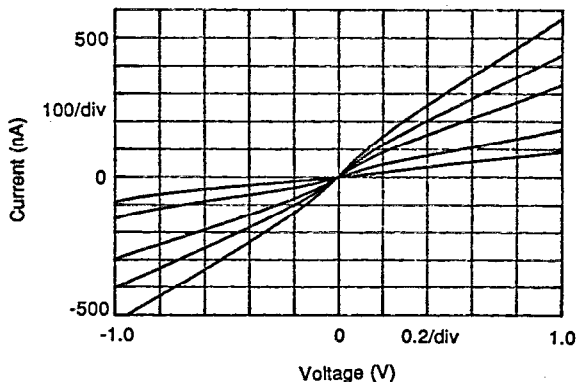


FIG. 2. Current-voltage characteristics of a GaAs MSM photodetector at different light intensities.

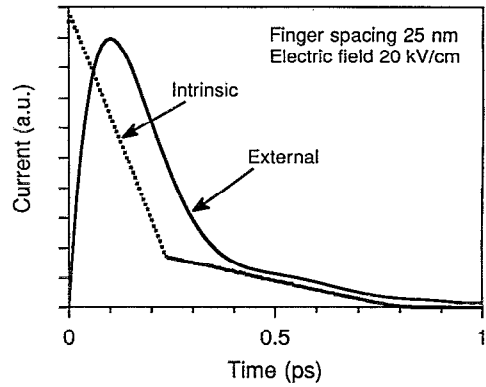


FIG. 3. Monte Carlo simulations of intrinsic and external current. The detector capacitance of 1.2 fF and load resistance of 50 Ω were used to calculate the external currents.

50 Ω and the device capacitance to be 1.2 fF. It assumes that the active area of the detector of 25 nm finger spacing and width is 1 $\mu\text{m} \times 1 \mu\text{m}$ and the capacitance per finger length is 0.06 fF/ μm .

The relation between the intrinsic response time and the finger spacing of a MSM photodetector is given in Fig. 5. It shows when the finger spacing is less than 0.3 μm , the response time decreases much faster than that for a larger finger spacing. This is due to the fact that when the finger spacing becomes comparable to the mean free path, electrons encounter less scattering and travel more ballistically. In the simulation, we assumed that the maximum velocity of carriers is the saturation velocity, 2×10^7 cm/s, which certainly can be an underestimation for the MSM photodetectors of sub-50 nm finger spacing, due to the electron velocity overshoot.⁷ This fast device operation due to carrier velocity overshoot is a unique feature of nano-scale MSM photodetectors.

The response time is strongly affected by the biasing electric field. The response time of MSM photodetectors with different finger spacing at different biasing fields is given in Fig. 5. At a low field, photon-generated carriers will move at a small drift velocity and give rise to a long transit time. With the smaller finger spacing, the detector can achieve its maximum speed at lower bias.

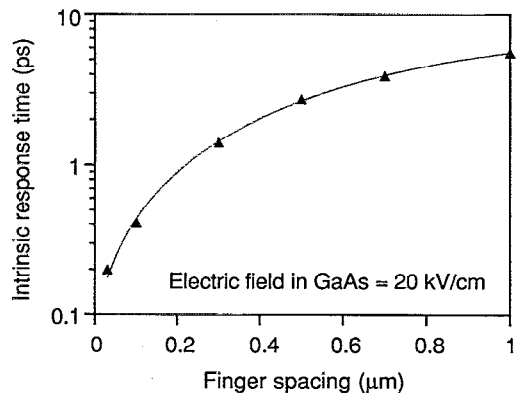


FIG. 4. Intrinsic response time vs the finger spacing.

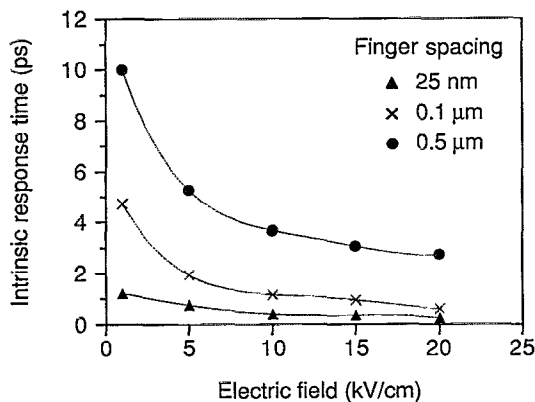


FIG. 5. Intrinsic response time vs average biasing electric field for MSM photodetectors with different finger spacing.

It is very important to point out that to achieve high-speed operation of a MSM photodetector, reducing finger spacing is just one of the factors; reducing finger width is another. The finger spacing determines the intrinsic response time of the detector; the ratio of the finger width to the finger spacing determines the detector capacitance and therefore external response time. The detector capacitance as a function of the ratio of finger width to the pitch (the sum of finger width and spacing) was calculated using conformal mapping⁸ and is shown in Fig. 6. It indicates that the smaller this ratio, the smaller the detector capacitance per finger length, and the faster the external impulse response. Therefore, proper scaling of MSM photodetectors for high-speed operation requires shrinking the finger spacing and the ratio of finger width to the finger spacing at the same time.

As the finger width becomes smaller, the detector series resistance can increase significantly and can be greater

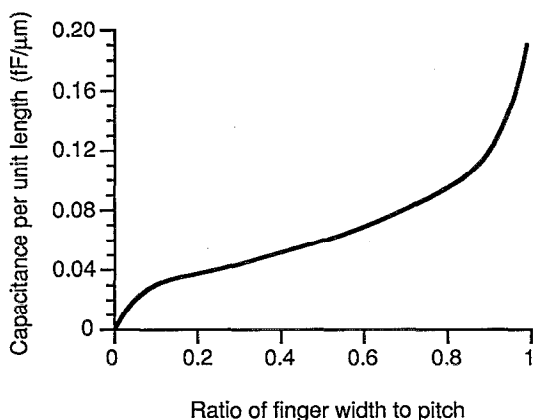


FIG. 6. Capacitance per unit length of a MSM photodetector vs the ratio of finger width to the period (the sum of the spacing and the width).

than the transmission line impedance (typically 50 Ω), playing a dominant role in limiting the detector speed. However, for a detector with $1 \mu\text{m} \times 1 \mu\text{m}$ active area and 25 nm finger width and spacing, its series resistance is about 40 Ω when the metal thickness is 50 nm (15 nm Ti and 35 nm Au). For reducing the finger resistance, thick metal fingers are preferred.

It should be pointed out, as required by the referee, that after the submission of the paper, Chen *et al.* reported a recombination-time-limited MSM photodetector with 0.2 μm finger spacing and width on low-temperature-grown (LT) GaAs, which has a response time of 1.2 ps and a 3-dB bandwidth of 375 GHz.⁹ Recently we have achieved 0.87 ps response time and 510 GHz 3-dB bandwidth in a MSM photodetector with 0.3 μm finger spacing and width on LT GaAs.⁶

In summary, using high-resolution electron beam lithography, we have fabricated MSM photodetectors with finger spacing and width as small as 25 nm, which are, to our knowledge, the smallest ever reported. Direct current measurements of the photodetectors showed low dark current and high sensitivity. Monte Carlo simulations show that the subpicosecond response time can be achieved as the finger spacing and width shrinks below 50 nm. For the 25 nm finger spacing MSM photodetector, the FWHM of the simulated intrinsic current response is 0.16 ps, but the real intrinsic time can be even shorter, because of velocity overshoot. The FWHM of the external impulse response of the 25 nm finger spacing MSM detector with a 50 Ω load resistance and 1.2 fF device capacitance is 0.25 ps; and the 3 dB bandwidth is 0.4 THz and can be over 1.8 THz if the hole current is reduced.

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