

# Ultrafast nanoscale metal-semiconductor-metal photodetectors on bulk and low-temperature grown GaAs

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Metal-semiconductor-metal photodetectors of finger spacing and width as small as 100 nm have been fabricated on bulk and low-temperature grown GaAs, and tested using a femtosecond pulse laser and high-speed electro-optic sampling. The fastest photodetectors have a measured full width at half maximum impulse response and a 3-dB bandwidth of 0.87 ps and 510 GHz, respectively, for low-temperature grown GaAs limited by carrier recombination time; and of 1.5 ps and 295 GHz for bulk GaAs, limited by the RC time constant. To our knowledge, they are the fastest detectors of their kinds reported to date.

Metal-semiconductor-metal photodetectors (MSM-PDs) can be classified into two types, depending on whether their speed is intrinsically limited by the carrier transit time or the carrier recombination time. However, the RC time constant of MSMPDs can become the limiting factor to the speed of the detectors of either type if it is greater than the transit time or the recombination time. Both types of MSMPDs on GaAs have been investigated by several groups.<sup>1-6</sup> The fastest transit time limited GaAs MSMPD reported previously had a finger width of 0.75  $\mu\text{m}$  and finger spacing of 0.5  $\mu\text{m}$ , an impulse response of 4.8 ps full width at half maximum (FWHM), a 3-dB bandwidth of 105 GHz.<sup>2</sup> The fastest recombination time limited MSMPD on low-temperature grown GaAs (LT-GaAs) reported previously had a finger width and spacing of 0.2  $\mu\text{m}$ , a FWHM of 1.2 ps and 3-dB bandwidth of 375 GHz.<sup>6</sup>

For ultra-high-speed applications, it is very desirable to minimize both finger spacing and width. The smaller the spacing, the shorter the intrinsic response time of the transit time limited MSMPDs and the higher the sensitivity of the recombination time limited MSMPDs; the smaller the finger width, the smaller the detector capacitance, leading to a smaller RC constant.<sup>7</sup>

In this letter, we report MSM photodetectors with nanoscale finger spacing and width, fabricated on bulk GaAs and LT-GaAs, that have faster FWHM impulse responses and higher 3-dB bandwidths than previously reported.

We fabricated nanoscale MSMPDs on two different substrates. One is semi-insulating GaAs, which has a resistivity of  $5 \times 10^7 \Omega \text{ cm}$  and electron mobility of  $6500 \text{ cm}^2/\text{V s}$ . The other substrate has a 1  $\mu\text{m}$  thick layer of LT-GaAs grown on SI-GaAs. The LT-GaAs was grown at 210 °C with a growth rate of 0.5  $\mu\text{m}/\text{h}$  and was annealed at 600 °C for 1 h. The metal fingers of the MSMPDs were defined using electron beam lithography and a liftoff process. Polymethylmetacrylate (PMMA) was spun on the substrates and baked, then interdigitated line patterns were exposed in the resist using a custom-built high-resolution electron beam lithography system converted from a JEOL-840 scanning electron microscope at a beam energy of 35

keV.<sup>8</sup> After resist development, Ti and Au of a total thickness of 50 nm were deposited on the wafer and lifted off in acetone. Although we have achieved 25 nm finger spacing and width,<sup>7</sup> the smallest detector finger spacing and width in these experiments is 100 nm. The detector area is  $10 \times 10 \mu\text{m}^2$  (Fig. 1). For high speed measurements, coplanar striplines with a linewidth of 16  $\mu\text{m}$ , a spacing of 9  $\mu\text{m}$ , and a quasistatic characteristic impedance of 75  $\Omega$  were fabricated on the substrate.

The MSMPDs were characterized using a high-speed electro-optic sampling system consisting of a 100 fs colliding pulse mode-locked dye laser with a wavelength of 620 nm and a repetition rate of 100 MHz.<sup>9</sup> The response of the MSMPDs was measured using a LiTaO<sub>3</sub> tip probe placed 250  $\mu\text{m}$  from the detectors.

MSMPDs on LT-GaAs with different finger spacings and widths—100, 200, and 300 nm—were tested. We found that the detector with 300 nm finger spacing and width had a FWHM of 0.87 ps (Fig. 2). The 3-dB bandwidth of the detector, calculated using  $0.441/(\text{FWHM})$ , is 510 GHz.

The impulse response time of the MSM photodetectors on LT-GaAs becomes progressively worse as the finger spacing and width become smaller; the FWHM is, respec-

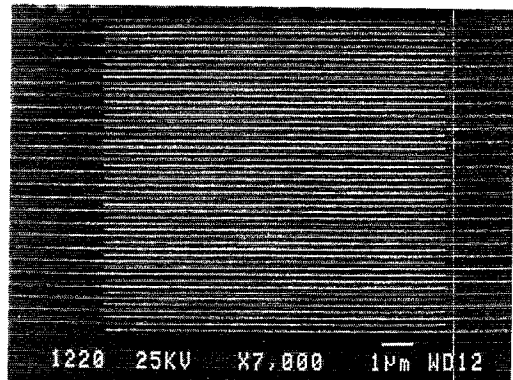


FIG. 1. Scanning electron micrograph of a MSMPD with finger spacing and width of 100 nm and an area of  $10 \times 10 \mu\text{m}^2$ .

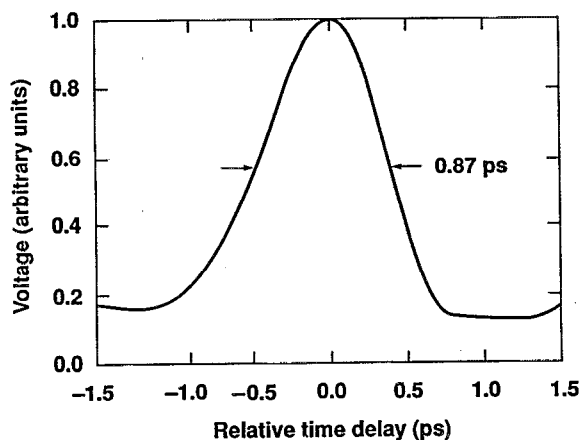


FIG. 2. The impulse response of a MSMPD on LT-GaAs with 300 nm finger spacing and width at 1.5 V bias.

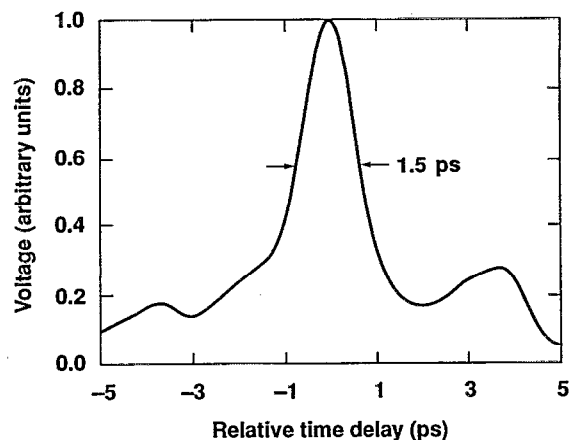


FIG. 3. The impulse response of a MSMPD on bulk GaAs with 100 nm finger spacing and width at 1.5 V bias.

tively, 1 and 1.6 ps for the MSMPDs of 200 and 100 nm finger spacing and width.

Furthermore, as the detector bias was varied from 0.1 to 3 V, the FWHM of all LT-GaAs MSMPDs does not change with the bias, indicating that these nanoscale MSMPDs on LT-GaAs are not transit time limited.

To understand the performance of these photodetectors, we tabulated the calculated intrinsic transit time, capacitance, RC constant, measured FWHM response time, and 3-dB bandwidth of these detectors in Table I. The intrinsic transit time is defined as the FWHM of the intrinsic impulse response of the detectors without recombination centers and was calculated using one-dimensional Monte Carlo simulation.<sup>7</sup> The detector capacitance was calculated using a conformal mapping method, which gives 0.06 fF/ $\mu\text{m}$  for a GaAs MSMPD with equal spacing and width.<sup>7</sup> The RC time constant of a photodetector is the product of the detector capacitance and the impedance of the transmission line. The RC time constant multiplied by 0.67 gives the FWHM of the impulse response of a RC circuit. The resistance of metal fingers is not significant in this case since it is smaller than the transmission line impedance.<sup>8</sup> The 3-dB bandwidths were obtained from the FWHMs and the formula given above.

As shown in Table I, for 300 nm LT-GaAs MSMPD, the measured FWHM is shorter than the intrinsic transit time but longer than the RC time constant multiplied by 0.67; therefore, its speed is dominated by the recombination time of the LT-GaAs. On the other hand, for LT-GaAs MSMPDs with finger spacing and width of 200 and 100 nm, the measured FWHM responses are longer than

0.87 ps—the response of recombination time limited PDs, and longer than the intrinsic transit time, but the same as 0.69 times of the RC constants. This implies that their speed is limited by the RC constants.

A MSMPD on bulk GaAs with 100 nm finger spacing and width was also tested. The measured impulse response has a FWHM of 1.5 ps (Fig. 3) and 3-dB bandwidth of 295 GHz. To our knowledge, this is the fastest MSMPD on bulk GaAs reported to date. The fact that this MSMPD has almost the same response time as that on LT-GaAs with the same device dimension indicates that the speed of this 100 nm MSMPD on bulk GaAs is limited by the RC constant. Table I predicts that if the RC constant can be reduced to a value less than the intrinsic transit time, the speed and the 3-dB bandwidth of a 100 nm MSMPD on bulk GaAs can be increased by a factor of 4.

The major difference between the impulse response of MSMPDs on bulk GaAs and LT-GaAs, as shown in Figs. 2 and 3, is that the MSMPD on bulk GaAs has a tail of 2-ps long. This tail is much shorter than the carrier recombination time in bulk GaAs, which is in the range of nanoseconds. This implies that, in contradiction to a general belief, the photogenerated carriers deep inside the semiconductor have rather insignificant contribution to the tail of the impulse response. Comparison with the Monte Carlo simulation results shows that, in fact, the long tail comes from the slow-moving holes. Finally, it was found that the MSMPDs on bulk GaAs is about a factor of 2 more sensitive than that on LT-GaAs.

In summary, we have fabricated MSM photodetectors on LT-GaAs and bulk GaAs with finger spacing and width

TABLE I. Calculation and measurement data of MSMPDs on LT-GaAs and bulk GaAs.

Semiconductor	LT-GaAs	LT-GaAs	LT-GaAs	Bulk GaAs
Finger spacing/width (nm)	100/100	200/200	300/300	100/100
Intrinsic transit time (ps)	0.4	0.8	1.1	0.4
RC(ln2) time constant (ps)	1.56	1.04	0.52	1.56
Measured response, FWHM, (ps)	1.6	1.0	0.87	1.5
3-dB bandwidth (GHz)	280	440	510	295

from 100 to 300 nm. The fastest MSMPD has a finger spacing and width of 300 nm, a FWHM of 0.87 ps, and a 3-dB bandwidth of 510 GHz; and its speed is limited by the recombination time. MSMPDs on LT-GaAs with finger spacing and width of 100 and 200 nm are slower than that for 300 nm, and their speed is limited by the RC constant. Furthermore, the MSMPDs on bulk GaAs with 100 nm finger spacing and width has a FWHM of 1.5 ps and a 3-dB bandwidth of 295 GHz, and its speed is limited by the RC constant.

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