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Nanoscale Sub-Picosecond Metal-Semiconductor-Metal Photodetectors

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Metal-semiconductor-metal photodetectors (MSM PDs) with finger spacing and width as small as 25 nm have been fabricated using high-resolution electron beam lithography on low-temperature-grown GaAs, bulk GaAs, and bulk Si. Measurement using an electro-optic sampling system showed that the fastest MSM PDs had finger spacing and width, full width at half maximum response time, and 3-dB bandwidth, respectively, of 300 nm, 0.87 ps, and 0.51 THz for LT-GaAs; 100 nm, 1.5 ps, and 0.3 THz for bulk GaAs; and 100 nm, 10.7 ps, and 41 GHz for crystalline Si. To our knowledge, they are the smallest and fastest MSM PDs ever reported. Monte Carlo simulation of detector response time is studied and compared with experimental data. Detector parasitic capacitance and resistance and their effects to the detector's speed are studied. Finally, scaling rules for high-speed MSM PDs are proposed.

1. INTRODUCTION

Recently, much progress has been made in high-speed metal-semiconductor-metal photodetectors (MSM PDs), since they are very attractive for optical communication, future high-speed chip-to-chip connection, and high-speed sampling.[1-9] MSM PDs can be classified according to whether their speed is intrinsically limited by the carrier transit time between the fingers or the carrier recombination time. Certainly, the speed of the detector will be limited by the RC time constant if it is larger than the transit time or the recombination time. It is desirable to make both finger spacing and width small in order to achieve high-speed operation.[9]

Previously, the fastest transit-time-limited GaAs MSM PD reported has a finger width of 0.75 μm and finger spacing of 0.5 μm, an impulse response of 4.8 ps full width at half maximum (FWHM), and a 3-dB bandwidth of 105 GHz.[4] The fastest recombination-time limited MSM PD on low-temperature-grown (LT) GaAs reported previously had a finger width and spacing of 0.2 μm, a FWHM of 1.2 ps, and a 3-dB bandwidth of 375 GHz.[6] The fastest MSM PD on crystalline silicon reported previously had a 4 μm single-gap and a 3-dB bandwidth of 22 GHz.[7]

In this paper, we report the fabrication and performance of nanoscale ultrafast MSM PDs on bulk and LT-GaAs, and crystalline Si, which have faster FWHM impulse responses and higher 3-dB bandwidths than previously reported. We present Monte Carlo simulation of the impulse response of nanoscale MSM PDs, and analyze the roles of electrons and holes to the performance of the PDs. The parasitic capacitance and resistance and their effects to device speed are analyzed. We also report the subpicosecond characterization of the nanoscale MSM PDs. Finally, we propose scaling rules for high-speed MSM PDs based on theoretical and experimental data.

2. FABRICATION

Three different substrates were studied: bulk GaAs, LT-GaAs, and crystalline silicon. The bulk GaAs was semi-insulating GaAs with carrier concentration of ~1.5×10^7. The LT-GaAs was 1 μm thick and grown at 210°C and annealed at 600°C for 1 hour. The Si substrate was p-type with a doping concentration of 8×10^{14} cm^{-3}. Coplanar striplines were defined photolithographically on the wafers for high-speed characterization of the detectors. Nanoscale metal fingers were fabricated using a custom-built electron beam lithography system and a lift-off process.[10] Fig. 1 shows the scanning electron micrographs of the nanoscale MSM PDs.

3. MODELLING AND SCALING

3.1. Monte Carlo Simulation

A Monte Carlo simulation program has been developed for simulating the intrinsic impulse response of transit-time-limited MSM PDs.[9] Fig. 2 shows the intrinsic response time vs. the finger spacing of transit-time-limited MSM PDs on GaAs and Si.

3.2. Parasitic Capacitance of MSM PDs

Parasitic capacitance of a MSM PD can be a limiting factor to its speed. Detector's capacitance was calculated using conformal mapping.[11] For a given detector area and finger pitch size, the smaller the finger width, the smaller the detector's capacitance.

3.3. Parasitic Resistance of MSM PDs

When the finger width is very narrow, the series resistance of metal fingers may become comparable to the load resistance and therefore increase RC time constant. We fabricated nanoscale metal lines on SiO_2 substrate and measured their resistances.[8] The thin

(a)

(b)

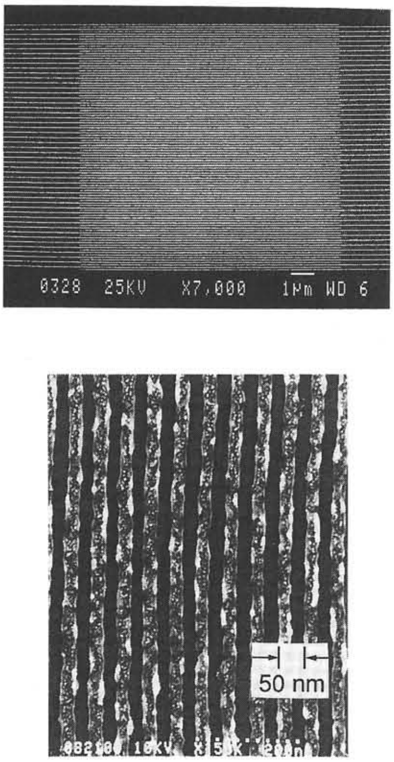

Fig. 1. Scanning electron micrographs of MSM PDs of (a) 50 nm finger width and 50 nm finger spacing, and (b) 25 nm spacing and 25 nm width. The metals are Ti/Au.

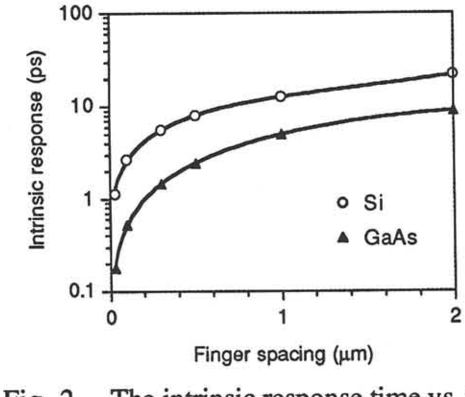

Fig. 2. The intrinsic response time vs. finger spacing on GaAs and Si MSM PDs.

metal line resistance is greater than that calculated from bulk resistance due to metal surface scattering. The detector total series resistance were therefore calculated from the measured line resistances.

3.4. Scaling Rules for High-speed Detectors

(1) For decreasing the intrinsic response time of transit-time-limited MSM PDs, the finger spacing should be reduced. (2) For reducing the MSM PD's capacitance, the ratio of finger width to finger spacing and/or detector's active area have to be reduced. (3) For cutting off the tails in the impulse response of MSM PDs, the hole current must be reduced or eliminated. And (4) for reducing metal finger resistance, it is preferable to use shorter fingers and thicker metal.

4. EXPERIMENTAL RESULTS

High-speed measurement was performed using an electro-optic sampling system consisting of a 100 fs colliding-pulse modelocked dye laser with a wavelength of 620 nm and a repetition rate of 100 MHz.[12)]

MSM PDs on LT-GaAs with different finger spacings and widths--100 nm, 200 nm, and 300 nm--were tested. The 300 nm detector has a FWHM of 0.87 ps (Fig. 3) and 3-dB bandwidth of 510 GHz. The impulse response time of the PDs becomes progressively worse as the finger spacing and width become smaller. We tabulated the calculated intrinsic transit time, RC time constant, measured FWHM, and 3-dB bandwidth of these detectors in Table I. The RC time constant is the product of the calculated detector capacitance and the impedance of the transmission line (75 Ω). The resistance of metal fingers is not important in this case because it is smaller than the transmission line impedance. As shown in Table I, for the 300 nm LT-GaAs MSM PD, the measured FWHM is shorter than the intrinsic transit time, but longer than RC time constant; therefore, its speed is dominated by the carrier recombination time of the LT-GaAs. On the other hand, for LT-GaAs MSM PDs with finger spacing and width of 100 nm and 200 nm, the measured FWHM responses are longer than 0.87 ps and the intrinsic transit time, but comparable to the calculated 0.67RC constants. This implies that they are limited by the RC time constant.

A MSM PD on bulk GaAs with 100 nm finger spacing and width was also tested. The impulse response has a FWHM of 1.5 ps (Fig. 4) and 3-dB bandwidth of 300 GHz. The fact that this MSM has almost the same response time as that on LT-GaAs with the same device dimension indicates that the speed of this 100 nm MSM PD on bulk GaAs is limited by the RC time.

Impulse response of a Si MSM PD with 100 nm finger spacing and width is shown in Fig. 5. The FWHM is 10.7 ps and the 3-dB bandwidth is 41 GHz. The response time of the Si detector is much longer than the estimated RC constant and the transit time. We suspect this is either due to leakage current since the active region is not isolated and the laser beam may illuminated the area outside the detector, or due to diffusion curent

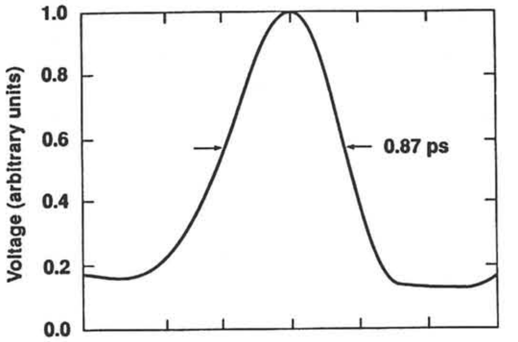

Fig. 3. Response of a LT-GaAs MSM PD with 300 nm finger spacing and width at 1.5 V bias.

Table I. Theoretical and experimental data of MSM PDs on LT-GaAs, bulk GaAs, and Si.

Semiconductor	LT-GaAs			Bulk GaAs	Bulk Si
Finger spacing/width (nm)	100/100	200/200	300/300	100/100	100/100
Intrinsic transit time (ps)	0.4	0.8	1.1	0.4	2.7
RC(*ln*2) time constant (ps)	1.56	1.04	0.52	1.56	1.56
Measured response (ps)	1.6	1.0	0.87	1.5	10.7
Measured bandwidth (GHz)	280	440	510	300	41

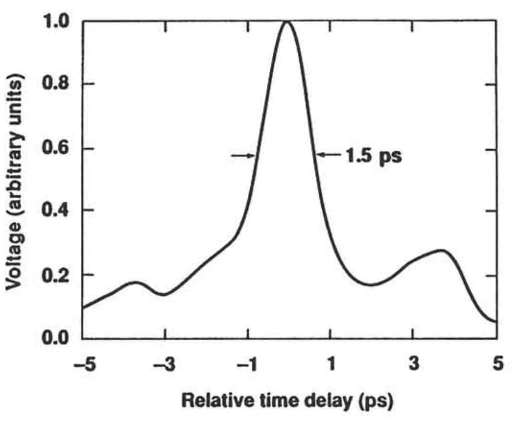

Fig. 4. Response of a bulk GaAs MSM PD with 100 nm finger spacing and width at 1.5 V bias.

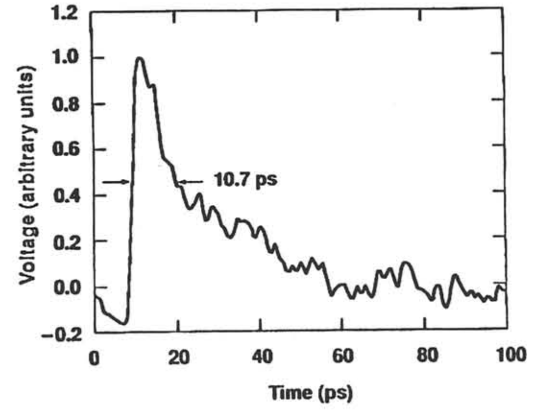

Fig. 5. Response of a Si MSM PD with 100 nm finger spacing and width at 1 V bias.

from the carriers generated deep inside the semiconductor since the light absorption length of Si is ~3 μm. Investigation is still in process. Nonetheless, to our knowledge, this is the fastest MSM PD on crystalline Si ever reported.

5. SUMMARY

In summary, using a costum-built electron beam lithography system, we fabricated MSM PDs with finger spacing and width as small as 25 nm on several semiconductor substrates. Sub-picosecond characterization using electro-optic sampling showed that the fastest MSM PDs had FWHM response times and 3-dB bandwidths, respectively, of 0.87 ps and 510 GHz on LT-GaAs; 1.5 ps and 300 GHz on bulk GaAs; and 10.7 ps and 40 GHz on bulk Si. Based on Monte Carlo simulation, calculation of capacitance and resistance, and experimental data, scaling rules for achieving high-speed MSM PDs were proposed.

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