Fabrication of sub-50 nm finger spacing and width high-speed metal–semiconductor–metal photodetectors using high-resolution electron beam lithography and molecular beam epitaxy

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Using high-resolution electron beam lithography, we have fabricated metal–semiconductor–metal photodetectors with sub-50 nm finger spacing and finger width on GaAs grown by molecular beam epitaxy, which are, to our knowledge, the smallest ever reported. Direct-current measurements showed that they have low dark current and high sensitivity. Proper scaling of the detectors to reduce the finger resistance and detector capacitance and to increase detector speed was studied. The resistances of thin metal lines with various widths were measured and compared with the value calculated from resistivity for bulk metal. Monte Carlo simulation demonstrates that for the photodetectors with 30 nm finger spacing and width, the response time is below picosecond and the cut-off frequency is over 1 THz.

I. INTRODUCTION

Metal–semiconductor–metal (MSM) photodetectors are very attractive for optical-fiber communication systems and high-speed chip-to-chip connections.[1–4] MSM photodetectors have several advantages over *p-i-n* photodiodes,[5] such as higher sensitivity-bandwidth product, simple fabrication, and compatibility with large-scale field-effect transistor (FET) integrated circuit technology. The operation of a MSM photodetector can be classified into two groups: recombination time limited or transit time limited. In the first group, the semiconductor must be heavily damaged to shorten carrier recombination time for high-speed operation at the expense of low sensitivity and less compatibility with FET integrated circuits fabrication. In the latter group, small finger spacing is utilized to decrease carrier transit time and increase device speed. Therefore, the photodetector has very high sensitivity-bandwidth product (about two orders of magnitude higher than recombination limited detectors) and can be built on high-quality semiconductor crystals. For ultrahigh-speed applications, it is very desirable to make spacing and width of interdigitated metal fingers of a transit time-limited MSM photodetector small.[6–8] The smaller the spacing, the shorter the intrinsic response time of the MSM photodetector; the smaller the finger widths, the less the detector capacitance and the shorter the external response time.

Previously, MSM photodetectors with finger spacing and width greater than 0.5 μm have been reported.[2,7–10] The fastest GaAs MSM photodetector was fabricated by Van Zeghbroeck *et al.*[10]; it has 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 an overall bandwidth of 105 GHz.

In this paper, we report on the fabrication of MSM photodetectors with finger spacing and finger width smaller than 50 nm, which are, to our knowledge, the smallest ever reported. The active GaAs layer is grown by molecular beam epitaxy, and the metal interdigitated electrodes are patterned by a high-resolution electron beam epitaxy. The dc measurements show that the devices have a low dark current (<40 nA at 0.5 V bias) and a high sensitivity (0.2 A/W). We also discuss the influence of finger resistance and device capacitance on high-speed operation.

II. FABRICATION

The MSM photodetector is shown schematically in Fig. 1. The devices 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 undoped layer is kept thin for reducing carrier transit time and increasing device speed. This may degrade the device sensitivity, however, when the active layer thickness becomes less than the characteristic light absorption length. For some high sensitivity applications, an AlGaAs/GaAs quarter-wave-stack reflector can be fabricated between the active layer and the substrate. The reflector plus an antireflection coating of the metal surface can improve the detector sensitivity drastically.

The metal (Ti/Au) Schottky barrier contacts were fabricated on GaAs by using electron beam lithography and a

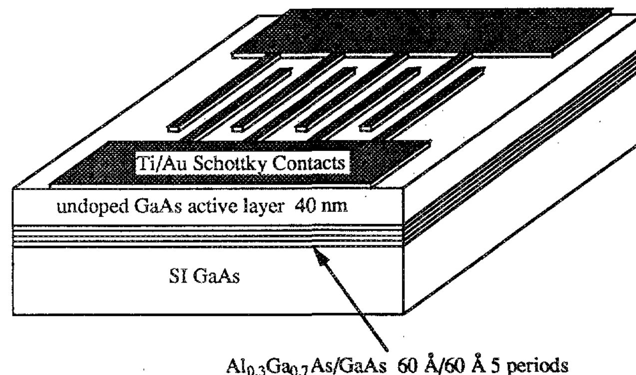

FIG. 1. Schematic view of a MSM photodetector. The pitch is equal to the addition of finger spacing and width.

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liftoff technique. Some of the photodetectors were patterned using two layers of polymethylmethacrylate (PMMA) spun on the GaAs layer with a high molecular weight (950 K) layer on top and a low molecular weight (100 K) layer at the bottom. The double-layer resist is used for achieving a good undercut profile suitable for the liftoff. Each layer of PMMA was baked at 160 °C for over 12 h after spinning. The finest MSM photodetectors were fabricated using a single 700-Å-thick layer of 950 K PMMA which was also baked for 12 h after spinning. 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 and at various doses, and developed in cellosolve:methanol (3:7) developer.[11] After exposure and development, metals (Ti/Au) were evaporated onto the samples and were lifted off in acetone. A total of 500 Å of metal was deposited when the bilayer resist was used, while a total of 300 Å of metal was deposited when the single-layer resist was used. Figure 2 shows the resulting metal linewidth as a function of dose for the MSM grating structures. The bilayer resist was found to be well suited for finger patterns with a pitch greater than or equal to 2000 Å. The undercut profile and thicker overall resist structure make it possible to use thicker metal fingers. In order to fabricate the devices with a 1000 Å finger pitch, however, a single-layer resist structure had to be employed. The basic fabrication steps are summarized in Fig. 3. Figure 4 shows scanning electron micrographs of MSM photodetectors with different active areas and finger structures; the smallest finger spacing and width are both 30 nm.

III. RESULTS

The dc characteristics of a GaAs MSM photodetector are shown in Fig. 5. The dark current of photodetectors is typically 40 nA at 0.5 V bias for a device area of 14.5 μm $\times$ 15 μm. The sensitivity of the devices is about 0.2 A/W. A passivation layer can be coated onto the devices to prevent surface oxidation and minimize the light reflection, therefore improving the dark current and sensitivity. The *I-V* characteristics do not show perfect saturation because of the surface recombination centers. An electrooptic sampling technique[12] is being used to study high-speed performance of the photodetectors.

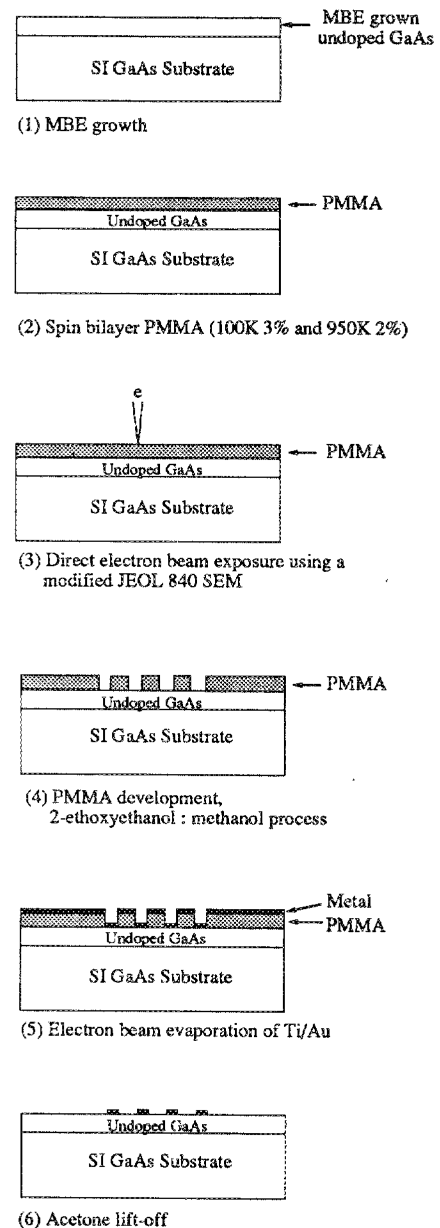


FIG. 3. Basic steps for fabricating sub-50 nm finger spacing and width MSM photodetectors.

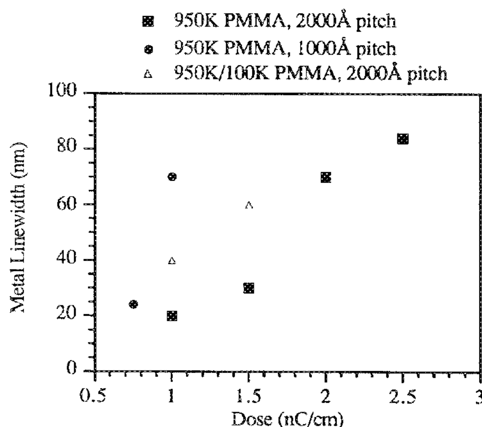
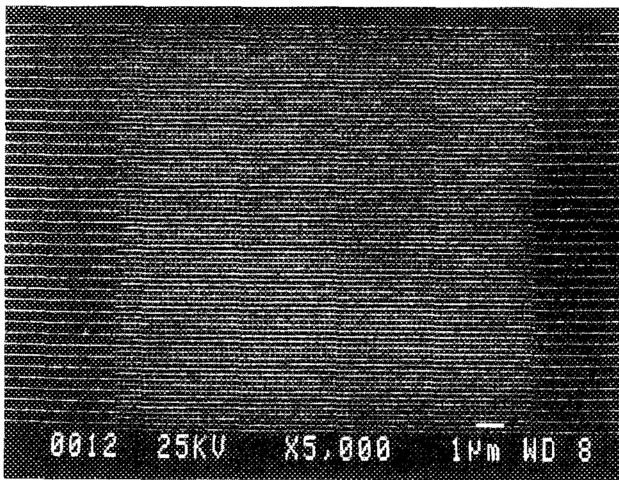
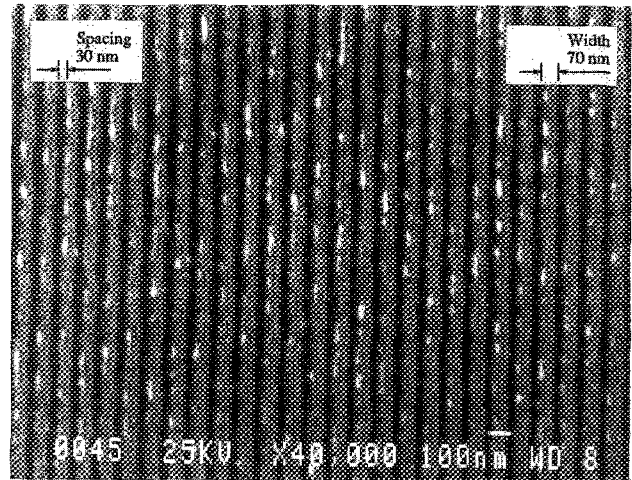


FIG. 2. Linewidth as a function of dose for the MSM grating patterns on GaAs substrates.

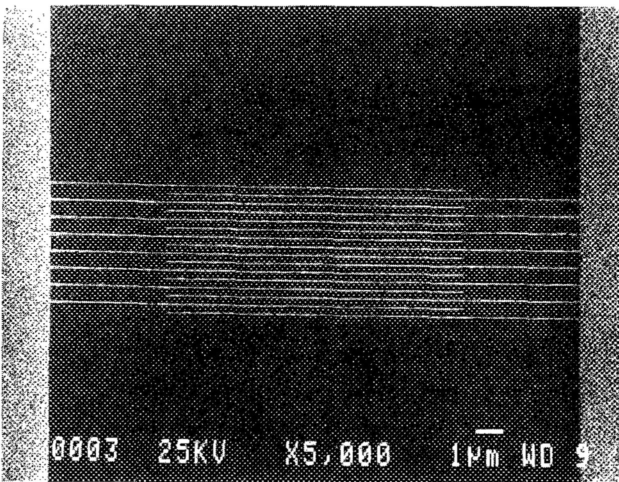
Monte Carlo simulation of the intrinsic impulse response of a MSM photodetector is shown in Fig. 6. The full width at half maximum (FWHM) of intrinsic impulse response is 0.2 ps for photodetector with 30 nm finger spacing. An external response is also shown when the detector capacitance of 1 fF and the load resistance of 50 Ω are used for calculation. Figure 7 shows the Fourier transform of the external response. The cutoff frequency of the photodetector is over 1 THz. The relation between the response time and the finger spacing is given in Fig. 8. When the finger spacing is less than 0.3 μm, the intrinsic response time decreases much faster than that for a larger finger spacing. This is due to the fact that when the finger spacing is so short, electrons encounter less scat-



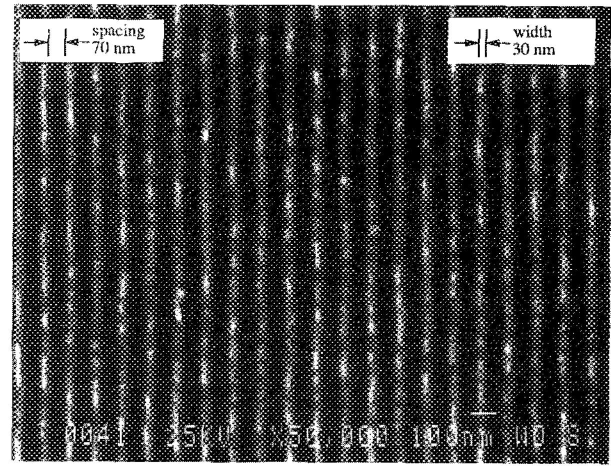
(a)



(c)



(b)



(d)

FIG. 4. Scanning electron micrographs of GaAs MSM photodetectors of (a) a 40 nm finger width and a 160 nm finger spacing, the total detection area is 14.5 μm $\times$ 15 μm; (b) a 50 nm finger width and a 250 nm finger spacing, the total detection area is 4.5 μm $\times$ 10 μm; (c) a 70 nm finger width and a 30 nm spacing; and (d) a 30 nm finger spacing and 70 nm width. The metals are Ti/Au.

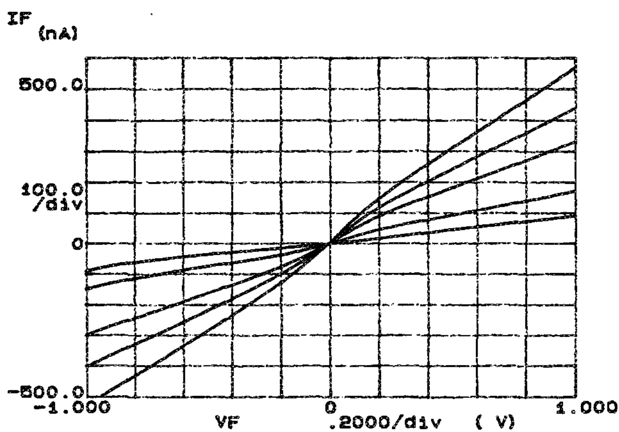


FIG. 5. Current-voltage characteristics of a MSM photodetector at different light intensities. Current is 100 nA/div and voltage 0.2 V/div.

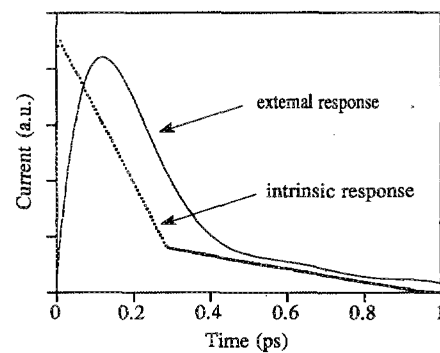


FIG. 6. Intrinsic impulse and external response of a MSM photodetector with 30 nm finger spacing. The electric field in GaAs is 20 kV/cm; the detector capacitance of 1 fF and the load resistance of 50 Ω are used for external response calculation.

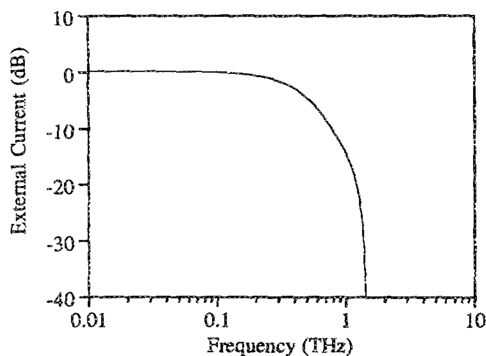


FIG. 7. Fourier transform of external current response as shown in Fig. 6(b).

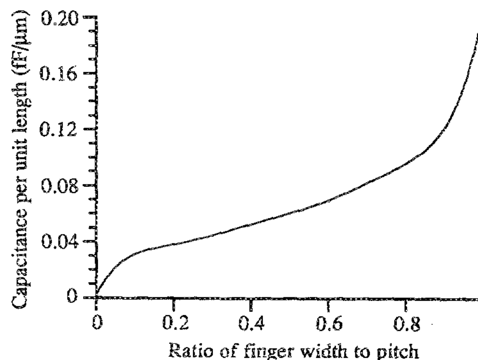


FIG. 9. Capacitance per unit length of a MSM photodetector vs the ratio of finger width to the pitch (i.e., the sum of the spacing and the width).

tering in GaAs and travel more ballistically. The velocity overshoot was not included in the simulation. In sub-50 nm photodetectors, the velocity overshoot can occur, leading to a higher operation speed.

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 the 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, the external response time. The detector capacitance as a function of the ratio of finger width to the period (which is the sum of the finger width and spacing) was calculated using conformal mappings[13] and is shown in Fig. 9. 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 finger widths become narrow, the resistivity of a metal finger is much greater than that of bulk material because of more collisions between electrons and the metal boundary. To study the resistance of thin metal lines, we fabricated metal lines of widths from 40 nm to 1.1 μm on SiO_2 substrate and measured their resistances. The SiO_2 substrate was used to reduce the leakage current between the contact pads, improving the measurement accuracy. Figure 10 shows the experimental results of the resistances as well as theoretical values calculated from bulk resistivities of Au and Ti. Clearly, to reduce the total device resistance for high-speed operation, thicker metal electrodes and shorter finger lengths are preferred. The ratio of the measured resistance of the metal wires to the theoretical one, plotted in Fig. 11, shows that the ratio is about 3.7 when the linewidth is wider than 0.1 μm, and it is doubled to 7.6 when the linewidth is narrower than 0.1 μm. This implies that when the linewidth is greater than 0.1 μm, the increase of resistance is due to the scattering caused by the thickness (50 nm in this case), and when the linewidth is less than 0.1 μm, the further increase of resistance is due to the additional scattering caused by the narrow linewidth.

IV. CONCLUSION

Using high-resolution electron beam lithography, we have fabricated MSM photodetectors with sub-50 nm finger spacing and width on MBE grown GaAs, which are, to our knowledge, the smallest ever reported. dc measurements of

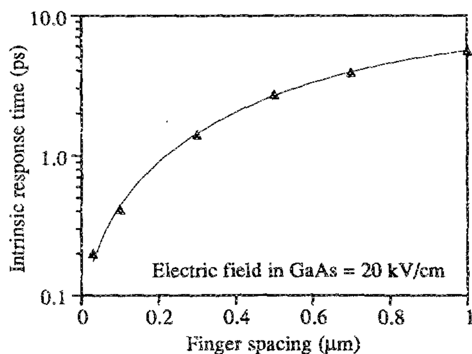


FIG. 8. Full width at half-maximum (FWHM) of intrinsic response time vs finger spacing.

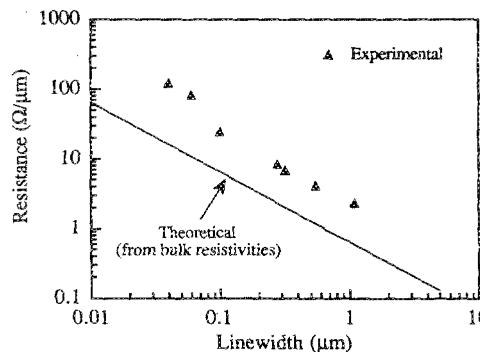


FIG. 10. Resistance per unit length vs linewidth. The metal is 35-nm-thick Au and 15-nm-thick Ti. ▲: Experimental data. Straight line: Resistance calculated from bulk resistivity.

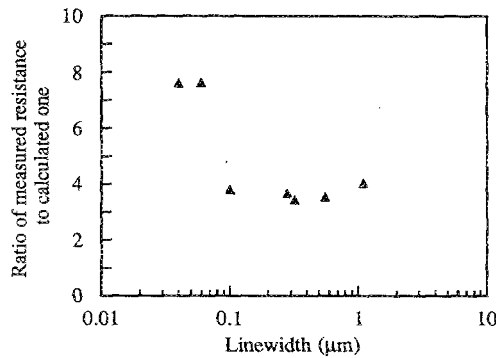


FIG. 11. Ratio of measured resistance to calculated one vs finger width. The metal thickness is 50 nm (35 nm gold and 15 nm titanium).

the photodetectors showed low dark current and high sensitivity. Monte Carlo simulation demonstrates that for MSM photodetectors with 30 nm finger spacing and width, the response time is below picosecond and the cutoff frequency is over 1 THz. The resistances of thin and narrow metal lines were measured and were found to be a factor of 4 higher than those calculated from the resistivity for bulk material. Furthermore, we found that when the linewidth becomes less than 0.1 μm, the resistivity of the metal line will be doubled. The study of scaling down MSM photodetectors shows that for high-speed application, the MSM detectors should have not only smaller finger spacing, but also small ratio of finger width to the finger period (sum of the finger width and spacing).

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