

# Polarimetry of thin metal transmission gratings in the resonance region and its impact on the response of metal-semiconductor-metal photodetectors

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The resonance behavior of metal transmission gratings and its impact on the response of metal-semiconductor-metal (MSM) photodetectors have been studied experimentally and theoretically. The metal gratings, with finger spacings in the subwavelength region of the visible light, were fabricated using *e*-beam lithography and lift-off. Strong resonances have been observed only in the *S* polarization. As a result, the light transmitted through a grating is primarily *S* polarized if the grating's finger spacing is less than one-third of the wavelength of the incident light, but *P* polarized otherwise. Similar phenomenon has been observed in the response of MSM photodetectors since the fingers (electrodes) of an MSM photodetector basically form a grating. Theoretical simulations employing the rigorous modal-expansion theory fairly predict the observed phenomenon. © 1997 American Institute of Physics. [S0003-6951(97)01818-4]

The investigation of grating polarizers started a century ago when Hertz discovered that a radio wave, after passing through a wire grating with spacing much smaller than the wavelength of the radiation, was polarized into the direction perpendicular to the grating's wires.<sup>1</sup> Since then the investigation of polarizers using transmission gratings has been carried out extensively over a broad spectral range. Grating polarizers have many advantages over other types of polarizers, for example, compactness, large acceptance angle, and wavelength insensitivity, making them ideal elements for optical integrated circuits (OICs) and optoelectronics. In addition to polarizers, transmission metal gratings can also be used as antireflection elements<sup>2,3</sup> and light couplers. Previously, studies on grating polarizers were carried out mostly on those fabricated by mechanical ruling, photochemical replication, and electroplating with typical thicknesses larger than 0.5  $\mu\text{m}$  (therefore, they are also called wire gratings). The applications in optoelectronics and OICs, however, require the gratings to be fabricated with a process compatible with that of microelectronic devices. On the other hand, the electrode (finger) periods of metal-semiconductor-metal (MSM) photodetectors with picosecond temporal responses have approached the resonance region—the periods are in the scale of the incident light wavelength.<sup>4–6</sup> Given the same periodic nature, the interdigitated fingers of an MSM photodetector should also have a similar polarization effect as a grating, which shall in turn affect the response of the detector. The polarization-dependent responses of MSM photodetectors have been studied by Kuta *et al.*<sup>7</sup> Their result was based on the comparison of two different parameters at different spectral ranges. One is the photocurrent of a MSM photodetector on a GaAs substrate when the photon energy is larger than the substrate's band gap. The other is the light intensity transmitted through the detector when it is smaller. However, these two parameters are basically not comparable, especially in the resonance region. As a result, their experimental data shows inconsistency in the resonance region.

In this letter, we report the experimental and theoretical studies of the resonance behavior in thin metal transmission gratings and MSM photodetectors in the visible and infrared region. The gratings and MSM photodetectors are fabricated by *e*-beam lithography and lift-off, a process compatible with that of microelectronic devices. The fingers of the gratings and detectors are made of 15/35-nm-thick Ti/Au with spacings ranging from 100 to 600 nm and a spacing-to-width ratio of 1:1.25. The active areas of both the gratings and detectors are  $26 \times 26 \mu\text{m}^2$ . The gratings are fabricated on

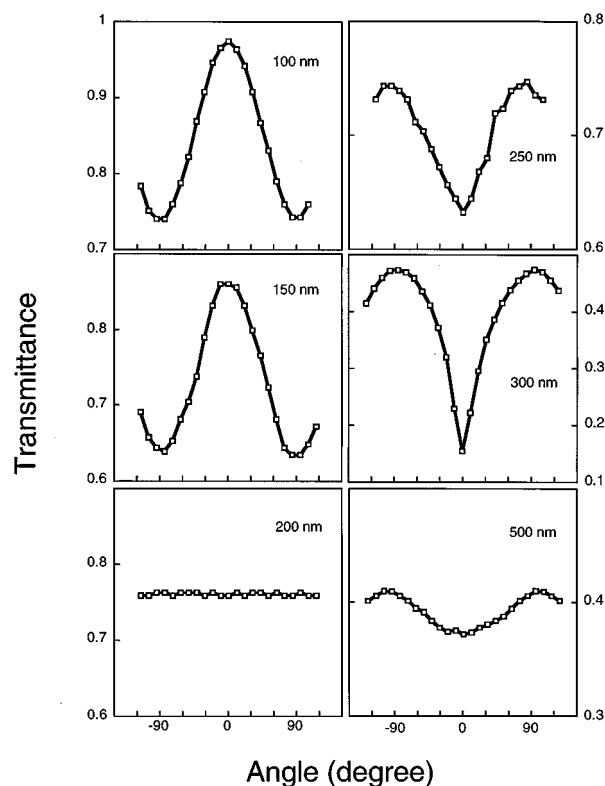


FIG. 1. The transmittances of the gratings on fused silica with spacings of 100–500 nm vs the polarization angle of the incident light at 0.633  $\mu\text{m}$  wavelength.

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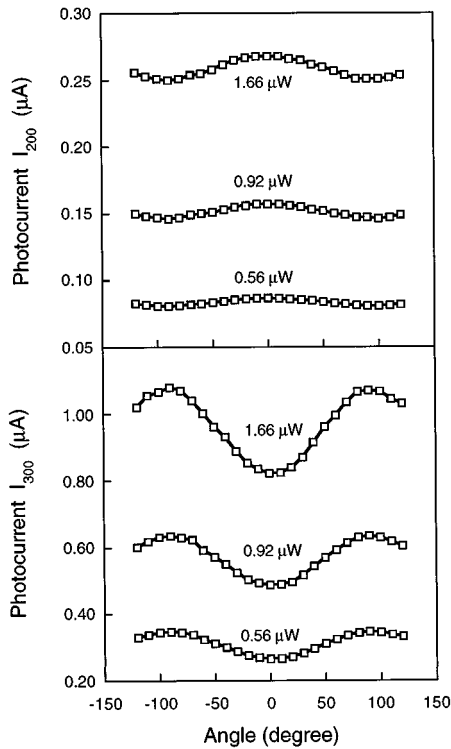


FIG. 2. The photocurrents of MSM photodetectors with finger spacings of 200 (top) and 300 nm (bottom) vs the polarization angle of the incident light at  $0.633 \mu\text{m}$  wavelength. The incident optical power is indicated on each curve.

0.1-mm-thick fused silica and the MSM photodetectors are fabricated on a semi-insulating GaAs (SI-GaAs) substrate. The thickness of the fingers is limited by our fabrication process. Since the gratings' finger aspect ratio is very small, their polarimetric behavior is expected to be quite different from that of wire gratings.

We first investigated the polarization-dependent transmittances of the gratings. The applied optical sources included a He-Ne laser operating at the wavelength of  $0.633 \mu\text{m}$  and a Nd:YAG laser operating at  $1.06 \mu\text{m}$ . A long-working-length objective focused the beam onto the grating surface within a diameter of approximately  $15 \mu\text{m}$ . In front of the objective was a broadband polarizer cube for ensuring a linear-polarized incident light. The transmitted light was then collected into a Si photodetector by a similar objective. Samples were mounted on a rotation stage with an angular resolution of  $1^\circ$ . A lock-in amplifier was used for the collection of data. The transmission of a plain 15/35-nm-thick Ti/Au film was measured to be less than 4%. Figure 1 shows the transmittances of the gratings as a function of the angle between the polarization of the incident light and the orientation of the gratings' fingers, measured at  $0.633 \mu\text{m}$  wavelength. This angle is defined as zero when the light is *S* polarized (i.e., the electric vector of the light is perpendicular to the gratings' fingers), and  $\pm 90^\circ$  when it is *P* polarized (the electric vector is parallel to the fingers). The transmittance is defined as the ratio of the light intensities transmitted through the substrates with and without the gratings. As shown in Fig. 1, when the spacing of a grating is less than 200 nm (about one-third of the light wavelength), the transmittance reaches a maximum at the angle of  $0^\circ$  and a mini-

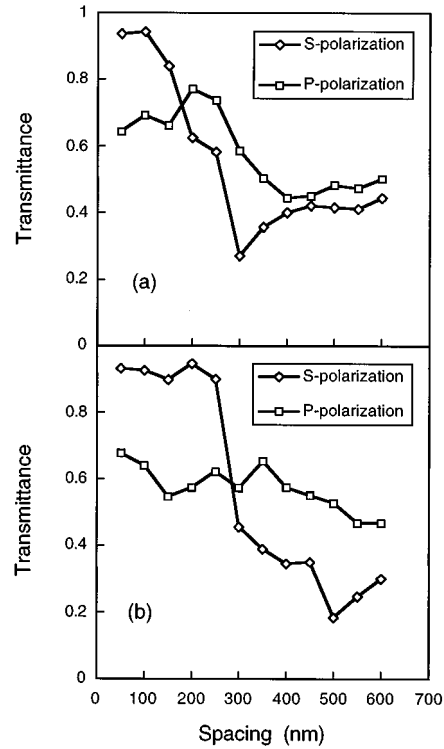


FIG. 3. The transmittances of the gratings vs their finger spacings at the wavelengths of (a)  $0.633$  and (b)  $1.06 \mu\text{m}$ .

mum at  $\pm 90^\circ$ , with a difference as large as 35%. However, for those gratings with spacings larger than one-third of the wavelength, the maximum and minimum transmittances occur at the angles of  $\pm 90^\circ$  and  $0^\circ$ , respectively, with a difference close to 60%.

Similar phenomena have been observed in the responses of the MSM photodetectors. For example, Fig. 2 shows the photocurrents of two MSM photodetectors with 200 and 300 nm finger spacings, biased at 2.0 and 3.0 V, respectively. At  $0^\circ$ , the response of the 200 nm photodetector reaches its maximum while that of the 300 nm one reaches its minimum, similar to the transmittances of the 200 and 300 nm gratings shown in Fig. 1. Since the SI-GaAs substrate has no contributions to the polarization effect, the above phenomenon is caused by the detectors' fingers.

The transmittances of the gratings at  $0.633$  and  $1.06 \mu\text{m}$  wavelengths are, respectively, plotted in Figs. 3(a) and 3(b) as a function of their finger spacings. At both wavelengths, the transmittance of the *S* polarization changes sharply with a minimum at a spacing equals to half of the wavelength. The transmittance of the *P* polarization, on the other hand, remains almost unchanged. The crossover between *S* and *P* polarization is at the finger spacing equal to one-third of the wavelength. To understand the phenomenon, a rigorous theory based on modal expansion<sup>8</sup> is applied. The results are plotted in Fig. 4 along with the experimental data. The theory indicates that the minimum in the transmittance of the *S* polarization is caused by a strong resonance of the optical radiation on the grating's surface when one of its diffracted orders becomes grazing (so called Rayleigh anomaly). This resonance occurs at the wavelength  $\lambda \approx d \approx 2a$  (Rayleigh wavelength), where  $d$  and  $a$  are, respectively, the period and

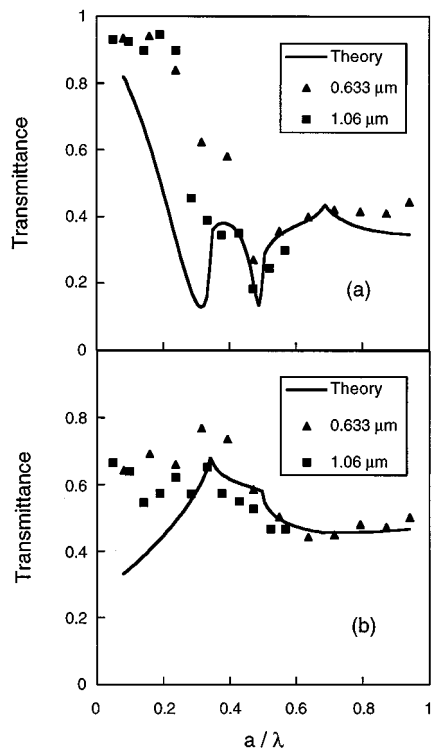


FIG. 4. The transmittances of the (a) *S* and (b) *P* polarization vs the gratings' spacing-wavelength ratio calculated using the modal expansion. Experimental data are also shown.

spacing of a grating. The resonance of the *P* polarization, on the other hand, is rather small since the grazing mode of this polarization is suppressed in a shallow grating.<sup>9,10</sup> Furthermore, unlike in a thick metal grating, the *P* polarization is not completely short circuited since the fingers are not perfect conductors and their thickness is rather small. As a result, the *P* polarization retains its intensity. It is the combination of the polarimetric effects in the *S* and *P* polarization that causes the observed phenomenon shown in Fig. 1. The theory also indicates a second resonance minimum in the *S* polarization at the spacing-wavelength ratio of  $a/\lambda = 1/2n$ , where  $n$  is the refractive index of the substrate (fused silica,

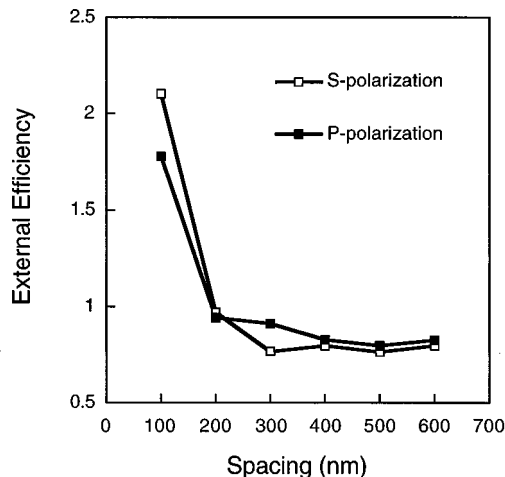


FIG. 5. The external efficiencies vs the spacings of the MSM photodetectors.

$n \approx 1.46$ ). This minimum, caused by the resonance of the optical radiation in the substrate, does not clearly appear in the experimental data, presumably due to lack of experimental points. Moreover, except the 10% discrepancy at the small spacing-wavelength ratio end ( $< 0.3$ ), the theory fits the experiment fairly well for both polarizations.

The external efficiencies of the MSM photodetectors, measured at  $0.633 \mu\text{m}$  wavelength with an incident optical power of  $57 \text{ nW}$ , are plotted in Fig. 5. Each detector was biased at its saturation voltage (the voltage at which the photocurrent of a MSM photodetector begins to saturate). Comparing Fig. 5 with Fig. 3 it is not hard to see that the external efficiencies of the detectors behavior similarly as the transmittances of the gratings. For example, there is also a minimum in the efficiency of the *S* polarization at a spacing of  $300 \text{ nm}$ . However, the difference between the efficiencies of the *S* and *P* polarization of the detectors is much smaller than the difference between the transmittances of the polarizations of the gratings. This is because the *S*-polarization excited surface modes generate part of the photocurrents in a MSM photodetector but have no contributions to the propagating orders of a grating. Furthermore, the external efficiency of the *S* polarization is larger than that of the *P* polarization when the spacing is less than  $200 \text{ nm}$ , just as the transmittance of a grating shown in Fig. 3. The detectors' over 100% efficiency is caused by the gain in the MSM photodetectors<sup>11</sup> which may increase as the spacing decreases.

In summary, the study of transmission thin metal gratings and MSM photodetectors reveals a strong resonance in the *S* polarization but not in the *P* polarization. As a result, a grating favors the transmission of the *S*-polarized light if its spacing is less than one-third of the incident light wavelength. However, if its spacing is larger than one-third of the wavelength, it favors the transmission of the *P*-polarized light. Since the electrodes of an MSM photodetector basically form a metal grating, resonance effect inherently exists in its response. As a result, the wavelength dependence must be included in calculating the transmittance of the fingers in an MSM photodetector gives when the detector's finger spacing is less than the wavelength of the incident light. Rigorous theories have to be applied in this region to give an accurate result.

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