Diffraction Grating Effect on Waveguided Germanium MSM Photodetector Response

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Germanium-on-silicon-on-insulator (Ge-on-SOI) photodetectors have been actively pursued for optical interconnection/communication applications because of its large absorption coefficient [1] and its integration compatibility with silicon (Si) complementary metal-oxide-semiconductor (CMOS) process technology. In particular, the metal-semiconductor-metal (MSM) configured photodiodes have been widely used due to its relative ease of fabrication and high speed performance [2,3]. Although the MSM configured detector may exhibit low quantum efficiency and large dark current as compared to the p-i-n detector, the latter can be successfully overcome by incorporating a Si:C Schottky-barrier enhancement layer [4] or by using sulfur-segregation at the NiGe/Ge interface to de-pin the Fermi level away from the valence band edge [5]. However, the illumination incident into the MSM photodetectors may be sensitive to the dimension of interdigitated metallic electrodes that acts as a one-dimension diffraction grating.

To date, there are only few studies focusing on this issue and our aim is to study the effect of the electrode diffraction grating in Ge Schottky MSM photodetectors on SOI substrate by varying the electrode periods from 1.7, 1.8, to 1.9 μm. Higher responsivity in MSM photodetectors indicate higher noise margin, wider allowance for smaller device design and also the elimination of amplifier.

The interdigitated structure acted as the metallic electrodes and a one-dimensional (1D) metallic rectangular grating above the Ge active region. The measurements were operated at near-infrared wavelength of 1.55 μm under transverse magnetic (TM) mode, because TM mode is more sensitive to diffraction grating than transverse electric (TE) mode [6]. A relatively low dark current was observed due to an effective hole barrier modulation by the Si:C Schottky barrier layer. Based on the optical near-field simulation, we analyzed the relationship between photocurrent and optical energy confined inside the Ge region, demonstrating the diffraction effect induced by the metallic grating.

Figure 1 shows a schematic structure of the Ge-on-SOI MSM photodetector proposed in this work. The device was fabricated on an 8-inch SOI wafer with a 2 μm thick buried oxide. Dry etching was used to form a Si waveguide 220 nm in thickness and 500 nm in width. After active window definition, a pure Ge film with ~500 nm thickness was allowed to grow in an ultra-high vacuum chemical vapor deposition (UHVCVD) reactor. A thin silicon-germanium buffer was adopted to reduce the formation of misfit dislocations by minimizing the lattice mismatch between the two heterostructure materials [4]. A crystalline Si:C interfacial layer of ~20 nm was then deposited on the Ge region to act as a Schottky barrier enhancement layer for effective dark current reduction. Subsequently, the SiO_2 passivation layer of 400nm was deposited and selectively dry etched to form contact hole. The metallization comprising of aluminum (Al) was deposited and patterned to complete the device fabrication.

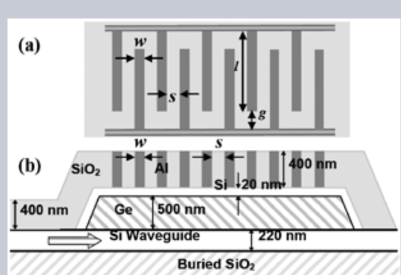

Figure 1: Schematic illustration of the Ge-on-SOI MSM photodetector with interdigitated metal electrodes. (a) Top view of the interdigitated fingers. (b) Cross-sectional view of the device structure.

Figure 1(a) depicts the top-view scheme of the interdigitated electrodes that formed a 1D metallic rectangular grating as shown from the cross-sectional viewpoint [Figure 1(b)]. The groove depth was having the same thickness of Al layer, which was fixed at 400 nm in this experiment. The finger width, spacing and periodicity were indicated by w, s, and $\Lambda = w + s$, respectively. Figure 2 shows the top-view scanning electron microscopy (SEM) image of our fabricated Ge-on-SOI MSM detector structure with an effective device width W of 25 μm and a length L of 50 μm, respectively. Due to a difference in the refractive index between Si and Ge, the incidence photon traveling in the Si waveguide would be up-coupled into the Ge region for absorption.

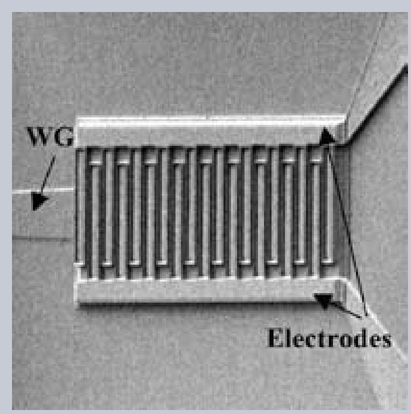

Figure 2: Top-view SEM image of the Ge-on-SOI MSM photodetector featuring interdigitated electrodes with an effective device width W of 25 μm and length L of 50 μm.

The photoresponse characteristics of the Ge-on-SOI MSM photodetectors were

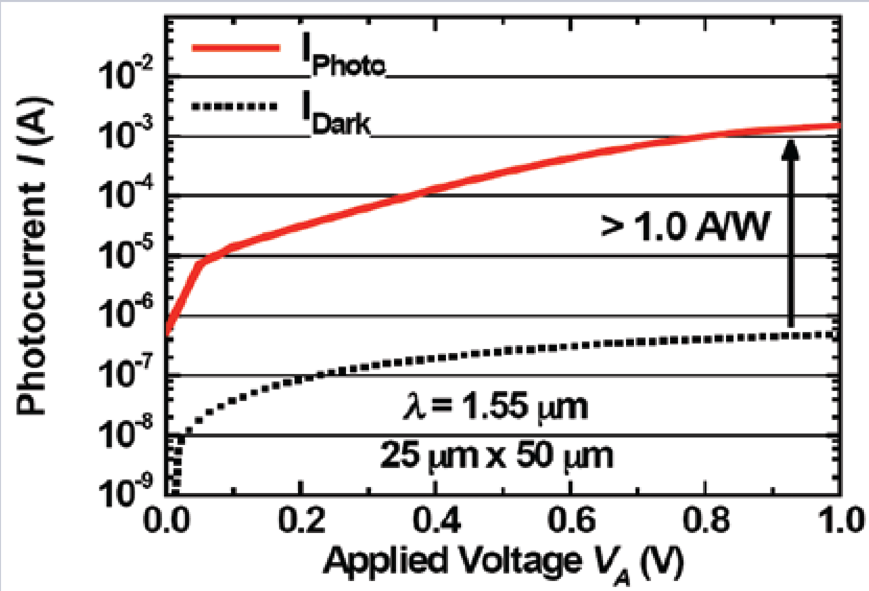

Figure 3: Photoresponse characteristics of a Ge-on-SOI interdigitated MSM photodetector with finger width w of 1.2 μm and spacing s of 0.6 μm. The optical measurement was performed by injecting a TM-mode incident electromagnetic (EM) wave with a wavelength λ of 1.55 μm into the Si waveguide and coupled into the Ge active region for absorption. The responsivity of the detector was calculated by subtracting the waveguide transmission loss of ~3.5 dB/cm and a coupling loss of ~4.5 dB.

plotted in Figure 3. The devices were featuring w of 1.2 μm and s of 0.6 μm. At an applied bias of 1.0 V, a low dark current of 0.5 μA (0.4 nA/μm²) was measured. This measurement was below the typical 1.0 μA generally considered to be the upper limit for high speed receiver design and consistent with the previous reported value on MSM devices [3]. The optical measurement was performed by injecting a TM mode incident electromagnetic (EM) wave with a wavelength λ of 1.55 μm into the Si waveguide and coupled into Ge active region for absorption. The incidence light power was estimated to be ~1 mW. At an applied bias of 1 V, the photocurrent was measured to be ~1.51 mA. The responsivities were well demonstrated to be over 1 A/W.

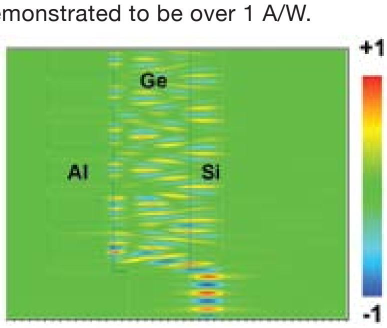

Figure 4: The normalized distribution of magnetic field under TM mode in a photodetector with finger width w of 1.2 μm and spacing s of 0.6 μm.

In order to evaluate the effect of the electrode diffraction grating on the response performance, the spatial distribution of the magnetic field in the structure based on the Finite-Difference Time-Domain method was calculated as shown in Figure 4, for a detector with a w of 1.2 μm and s of 0.6 μm. It was noted that the optical field appeared to be locally concentrated beneath the electrodes attributed to the diffraction grating effect of metallic electrodes.

To further confirm the impact of the metallic grating, we compared the measurement and simulation results for samples with varied electrode width w of 1.2, 1.3, and 1.4 μm (period Λ corresponding to 1.7, 1.8, and 1.9 μm) under TM modes, as shown in Figure 5(a) and 5(b). The spacing width s was fixed at 0.5 μm to maintain the same lateral spacing between the two adjacent fingers. The other structural parameters such as l and g (refer to Figure 1) were designed to ensure the same order dark current density. Photocurrent measurements were performed at an applied bias of 1 V. In Figure 5(b), we integrated the optical energy localized in the whole Ge active layer for these three dimensions.

By comparing Figure 5(a) with 5(b), the measured photocurrent showed good consistency with the simulated optical energy. The extent of confinement and resonant quality factor due to the diffraction effect was shown to exhibit strong dependence on the finger width geometry, which in turn resulted in a difference in the photon absorption. During the process of simulation, we assumed there were no optical absorption by the Ge layer so that we could estimate the optical energy inside the active region.

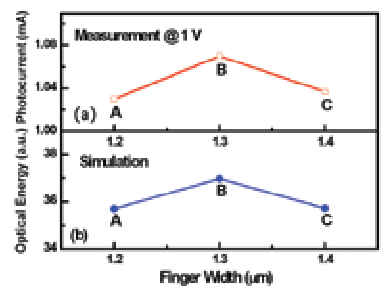

Figure 5: Effects of the electrode diffraction grating on the detector's photoresponse. (a) is the photocurrent measurement results at an applied bias of 1 V. (b) shows the calculated optical energy confinement within the Ge region.

In summary, Schottky interdigitated Ge-on-SOI MSM photodetectors with various finger width were fabricated with low dark current leakage. The photoresponse exhibited strong dependence on the finger width geometry, and showed good consistency with the numerical simulation. The results imply that the occurrence of optical energy localization beneath the metallic electrodes is beneficial to achieve higher photoresponse, which allows simultaneous achievement of high-speed response and sufficient responsivity in a small semiconductor element.

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