Leakage suppression by asymmetric area electrodes in metal-semiconductor-metal photodetectors

Ali K. Okyay,[a] Chi On Chui,[b] and Krishna C. Saraswat
Department of Electrical Engineering, Stanford University, Stanford, California 94305

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We have studied the effect of varying electrode area asymmetry on the leakage behavior of metal-semiconductor-metal photodetectors (MSM-PDs). We demonstrate, an effective suppression of dark current (I_{dark}) with the application of asymmetric electrode area and appropriate biasing scheme in MSM-PDs. More than 2× reduction in I_{dark} is obtained in photodetectors fabricated on silicon. Photoresponse of these detectors have also been monitored and normalized photo-to-dark current ratio (NPDR) metric is utilized for objective assessment of detector performance. Significant enhancement in NPDR is shown to be accomplished with the asymmetric Si MSM-PDs. © *2006 American Institute of Physics*. [DOI: 10.1063/1.2171648]

Optical clocking is promising to alleviate many limitations of large multi-gigahertz digital integrated circuit (IC) chips.[1] It is desirable to build the receiver of the optical link next to the biasing and amplification circuitry in order to avoid parasitic effects. High efficiency photodetectors compatible with Si process technology are always sought after in order to realize receivers on dense integrated systems. Among photodetector structures, metal-semiconductor-metal photodetectors (MSM-PDs) are attractive for their high sensitivity-bandwidth product, low capacitance, and ease of integration. However, relatively large photodetector dark current (I_{dark}) poses additional power dissipation as an increasingly serious problem especially in today's dense integrated systems and already very hot chips. In addition, the photodetector noise level (i.e., I_{dark}) due to self-heating is increased demanding higher optical powers for minimum detectable signal. Incorporation of a wide band gap layer at the metal-semiconductor (MS) contact interface to reduce I_{dark} was demonstrated on compound semiconductor MSM-PDs.[2] Application of asymmetric work function electrodes to significantly suppress I_{dark} by tailoring the MS barrier heights was also demonstrated.[3–5] In this letter, we report the effects of unequal contact areas on MSM-PD performance, particulary on I_{dark} suppression.

On a basic MSM structure with two back-to-back Schottky diodes, we have investigated the possibility to suppress leakage current by utilizing unequal-area contacts. Under an applied potential, an identical current flows through the electrodes to satisfy the current continuity requirement. The current density (J) at the small-area contact exceeds that of the larger contact. The higher J is accompanied with larger electric field widening the depletion layer around the smaller-area contact encroaching towards the larger one. This in turn decreases the reach through voltage, the bias voltage at which the sum of the depletion widths would extend through the electrode separation (i.e., total depletion operating condition).

Two-dimensional simulations of Si-based interdigitated MSM structures were carried out using MEDICI™ to verify I_{dark} reduction with the area asymmetry scheme. Total contact area and electrode spacing is kept constant while varying the asymmetry. Figure 1 plots detector current without illumination versus contact area asymmetry—defined as the ratio of electrode areas—showing reduction in current with increasing asymmetry.

MSM-PDs with a range of contact area asymmetries were fabricated on lightly doped ($\sim 10^{15}$ cm^{-3}) p-type Si wafers with (100) surface orientation. Native oxide was removed by dilute HF followed by metal (electron)-beam evaporation and photoresist lift-off for patterning the electrodes. 150 Å of Ti and 350 Å of Au stack was used as metal electrodes. Ti was chosen as the contact metal because its work function is close to midgap of Si providing high injection barriers for both electrons and holes at the Schottky contacts. Moreover, Ti is a very good adhesion layer to Si and Au is used for enhanced electrical probing. No heat treatment was performed to avoid interdiffusion and alloying between semiconductor and metal. Figure 2 shows a scanning electron micrograph (SEM) of one such MSM detector. Circular geometry detectors was employed to avoid secondary effects such as fringing fields and obtain uniform field distribution.

I-V measurements were taken with the bigger electrode grounded and the smaller one positively biased. Such con-

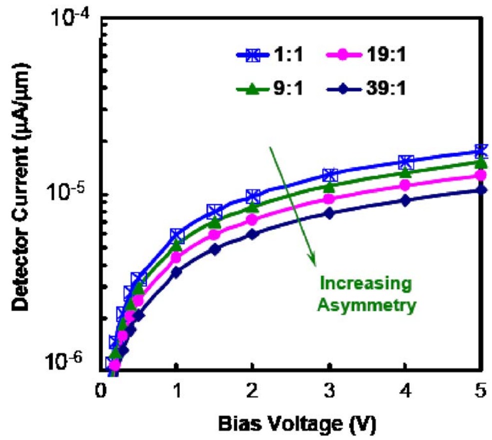

FIG. 1. (Color online) Simulation results for fixed total contact area photodetectors with varying electrode asymmetry. Simulations were done on a MSM structure per unit width with 1 μm interelectrode spacing and 5-μm-thick Si substrate.

[a]Electronic mail: aokyay@stanford.edu
[b]Present address: Intel corporation, Santa Clara, CA 95054.

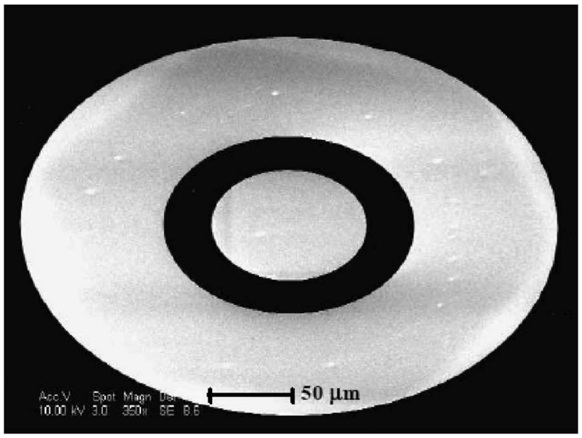

FIG. 2. SEM image of an asymmetric contact area MSM photodetector on Si.

figuration reversely biases the latter electrode as the substrate is lightly doped p-type Si. Dark I-V measurement results for such bias polarity are illustrated in Fig. 3. Photodetector species S_8-S_{12} have fixed electrode spacing, but varying contact area asymmetries as indicated in Fig. 3. I_{dark} is highest for S_{12} and is reduced toward the most asymmetric case, S_8. The trend plotted in Fig. 4 shows the leakage of the earlier photodetectors at a fixed voltage bias of 3 V after total contact area is normalized. Considerable I_{dark} drop $(2\times)$ is obtained

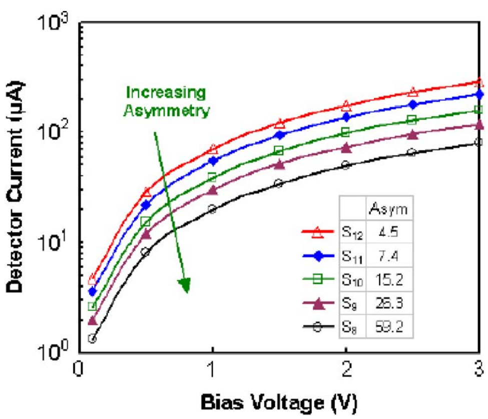

FIG. 3. (Color online) Experimental I-V under dark conditions. Dark current decreases from S_{12} to S_8 in the same direction as increasing area asymmetry.

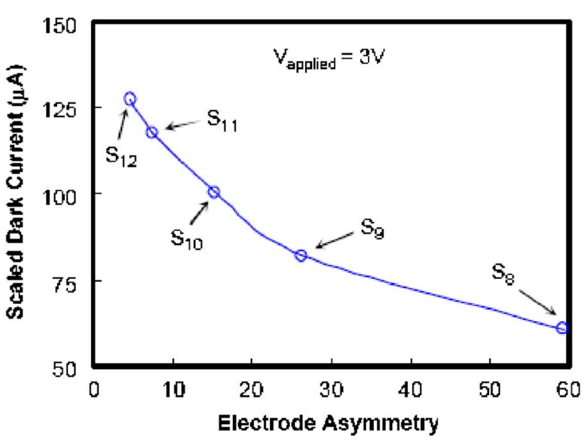

FIG. 4. (Color online) Scaled dark current vs electrode asymmetry at 3 V bias for normalized total contact area, and constant electrode separation.

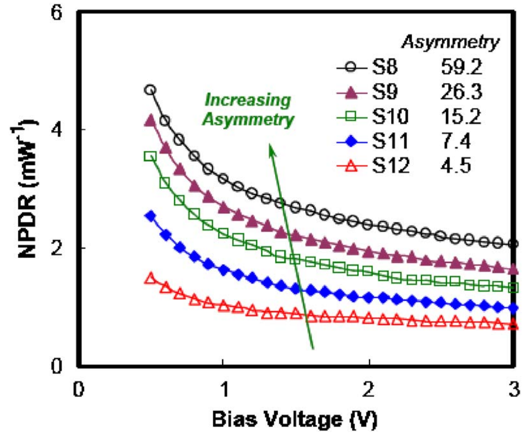

FIG. 5. (Color online) NPDR extracted under 632 nm illumination. NPDR is higher for larger asymmetry photodetectors due to reduced dark current with increasing electrode asymmetry and no significant degradation in photoresponse.

at 3 V bias for photodetectors with identical total electrode area and spacing, but varying contact area asymmetry.

Photoresponse of the detectors is also investigated for performance evaluations as an optically controlled electronic switch. Ratio of detector photocurrent to dark current normalized to the input optical power (NPDR) was introduced in an earlier work[5] as an objective metric for performance assessment in addition to I-V characteristics. NPDR provides direct information about photodetector responsivity and noise equivalent power through I_{dark}. Photodetectors were illuminated by red light $(\lambda \sim 632$ nm) and the photocurrent was monitored while the beam was translated relative to the electrodes. For fair comparison, measurements were recorded at the beam location corresponding to the highest photoresponse for each detector. Responsivity values of ~ 0.2 A/W were obtained with no significant degradation to the light-on state. NPDR versus applied bias is plotted in Fig. 5 representing clear enhancement of NPDR with electrode area asymmetry. The major contribution to the increase in NPDR is attributed to effective I_{dark} suppression by the proposed asymmetric electrode scheme without compromising the photocurrent.

We have demonstrated the application of asymmetric area electrodes in MSM-PDs to effectively suppress dark current. Improvement in NPDR by a factor of up to 3 was demonstrated with the asymmetric MSM-PDs. We believe that these results are particularly important and promising for its potential applications in low power and voltage photodetectors for densely integrated optoelectronic ICs.

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