GeSi APD with Ultralow Dark Currents for LiDAR

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***Abstract*—We report the fabrication and characterization of a 50-µm diameter GeSi avalanche photodiode (APD) in normal incidence configuration. The dark currents at unity gain and gain of 10 are measured to be 0.24 nA and 2.4 nA, respectively, demonstrating roughly 2 and 3 orders of magnitude reduction compared to the previously reported Ge-on-Si APDs, and out-performing many of the corresponding group III-V APDs in the literature. 3D point cloud (PCL) images are taken using the fabricated GeSi APD as proof of concept for time-of-flight (TOF) based light detection and ranging (LiDAR).**

Keywords—GeSi, APD, TOF, LiDAR

I. Introduction

APDs have long been applied in high-speed optical communication as well as in optical remote sensing. In particular, separate-absorption-charge-multiplication (SACM) APD has been a major device of interest because the materials for optical absorption and electrical multiplication can be individually chosen and engineered. At SWIR wavelengths, two main types of material groups, i.e., group III-V semiconductors such as InGaAs-on-InP [1] or InGaAs-on-InAlAs [2], and group IV semiconductors such as Ge-on-Si [3,4,5], have been used for fabricating SACM APD. Generally, InGaAs-on-InP-or-on-InAlAs has a lower dark current shot noise due to better lattice match compared to Ge-on-Si. On the other hand, Ge-on-Si has a lower avalanche gain excess noise due to smaller electron-to-hole impact ionization ratio compared to InGaAs-on-InP-or-on-InAlAs. For high-speed optical communication typically operating at 10 Gbps or faster, due to the large noise associated with transimpedance amplifier (TIA), the dark current shot noise of conventional Ge-on-Si APD may be less critical. Along with the low-cost benefit of manufacturing Ge-on-Si compared to InGaAs-on-InP-or-on-InAlAs due to starting wafer size difference, conventional Ge-on-Si APD has become a popular choice for high-speed optical communication. However, for optical remote sensing typically operating at a few hundreds of MHz or lower, the dark current shot noise of conventional Ge-on-Si APD becomes unbearable compared to the reduced TIA noise, so that conventional InGaAs-on-InP-or-on-InAlAs APD is still predominately applied despite its high-cost.

In this paper, we demonstrate a GeSi APD having dark currents lower than those of conventional Ge-on-Si APDs by orders of magnitude and even lower than those of conventional InGaAs-on-InP-or-on-InAlAs APDs, showing that the demonstrated GeSi APD is a leading contender for short-wavelength-infrared (SWIR) sensing and imaging in which best-in-class receiver sensitivity can be achieved through CMOS compatible technology.

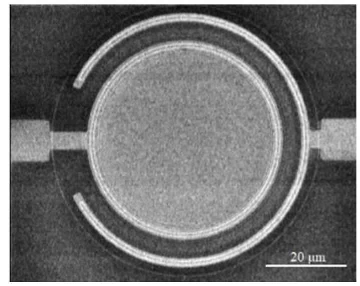

Fig. 1. Top view SEM image of the fabricated GeSi APD. The outer and inner metal rings connect to the N-contact and P-contact doping regions, respectively.

II. Device Fabrication and Characterization

The top-view scanning-electron-microscope (SEM) image of the fabricated GeSi APD with 50 µm diameter mesa and 45 µm diameter window is shown in Fig. 1. The mesa is formed through optimized epitaxial conditions to minimize the bulk threading dislocations due to lattice mismatch, and optimized etching and passivation conditions to minimize the surface dangling bonds. The outer and inner metal rings connect to the N-contact and P-contact doping regions, respectively. In Fig. 2(a), we plot the measured IV curves under light-on and light-off conditions using 1310 nm laser. The fabricated device features an ultralow dark current of 0.24 nA at unity gain at -9.5V, which is determined by a 4 µA photocurrent from a reference GeSi PD, i.e., same as the GeSi APD but without charge layer. The dark current at gain of 10 is then determined to be 2.4 nA, which is exactly 10 times the value at unity gain. Such a result implies the primary dark current, i.e., the dark current component that can be amplified by the multiplication region, dominates the total dark current and the unwanted un-multiplied dark current component is negligible. Indeed, by plotting the photo and dark gains (defined by how photo and dark currents increase relative to unity gain point) as a function of voltage in Fig. 2(b), we observe the two curves overlap nicely up to gain ~15. The breakdown voltage is determined to be -10.66 V by using 10 µA dark current criterion. The primary responsivity is measured to be 0.26 A/W from the reference GeSi PD.

To benchmark the performance of our GeSi APD, we compare APDs based on SACM in the literature [1-5] in Table 1. It can be seen that our GeSi APD features the lowest dark currents at unity gain and gain of 10, and demonstrates roughly 2 and 3 orders of magnitude reduction compared to group IV APDs [3,4,5] and even out-performs group III-V APDs [1,2]. Moreover, except for our GeSi APD, the un-wanted un-multiplied dark current components are not negligible and significantly increases with voltage applied. On the other hand, our primary responsivity is somewhat lower than these reported APDs due to a thin 450nm GeSi layer, which was chosen to lessen the efforts on topography related process tunings and can be improved in the future.

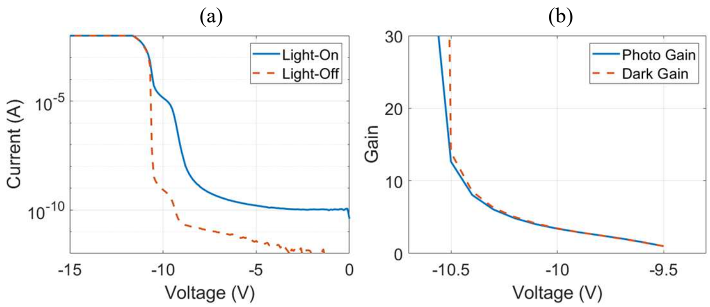

Fig. 2. (a) Current-voltage curves measured under light-on and light-off conditions. (b) Gain curves derived from photocurrent and dark current data.

TABLE I. COMPARISON OF APDS

	Device Diameter (μm)	Dark Current (nA) @ Unity / ×10 Gains	Responsivity (A/W) @ Unity Gain	Breakdown Voltage (V)
Ref. [1]	45	0.7 / 20	0.59 @ 1550nm	-34.28 @ 10uA
Ref. [2]	30 (Zn diffusion defined)	10 / 17	0.95 @ 1550nm	-29 @ 100uA
Ref. [3]	30	20 / 2000	0.55 @ 1310nm	-25 @ 10uA
Ref. [4]	30	200 / 1000	0.3 @ 1550nm	-29.4 @ 100uA
Ref. [5]	35	20 / 2000	0.9 @ 1550nm (cavity enhanced)	-28.5 @ 100uA
This Work	50	0.24 / 2.4	0.26 @ 1310nm	-10.66 @ 10uA

III. MODULE PREDICTION AND SYSTEM PROOF OF CONCEPT

In Fig. 3, to predict the module performance when a TIA is used in conjunction with APDs, we calculate the noise-equivalent power (NEP) as a function of gain. Avalanche gain excess noise is calculated by using McIntyre's formula. Input-referred noise of the TIA for LiDAR is assumed to be a typical value of 1 pA/sqrt(Hz). All device dark currents are normalized to the area of 50 μm diameter. To emphasize on the impact of noise and provide a fair comparison, we presume quantum efficiency (QE) of 50% at 1550 nm wavelength for all APDs in comparison. The minimal NEPs at the optimal gains for Ref. [3], [1], and this work are determined to be 1084, 215, and 75 fW/sqrt(Hz), respectively, showcasing the performance of our GeSi APD due to its ultralow dark currents.

As proof of concept, we set up a LiDAR system with the fabricated GeSi APD and a TIA to record 3D PCL data. A co-axial configuration aligning the transmitter and the receiver is chosen for the ease of demo, in which Galvo mirror/controller are used for steering 1550 nm pulsed laser beam, and oscilloscope is used for determining TOF. The pulsed laser width is 1 ns at 100 kHz repetition rate. The beam waist on the Galvo mirror is ~3.6 mm. The lens is 1 inch in diameter and 40 mm in focal length. The scanning field of view is 27 deg in both horizontal and vertical directions. In Fig. 4(a), the red-green-blue (RGB) image of the scene including the lab hallway is shown. Then, in Fig. 4(b), the corresponding PCL image is shown, and clearly highlights key 3D objects such as the sidewalls of the hallway, the two people standing at two different distances, the features over the roof, and the stop wall at the end of the hallway way. It is also observed that due to the specular (instead of Lambertian-like) reflection from smooth surface at a direction away from the LiDAR system, some 3D objects such as the tiles on the floor are harder to capture.

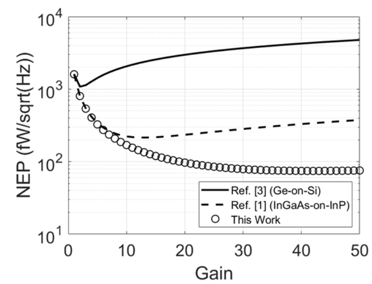

Fig. 3. NEP calculated as a function of gain at 1550 nm wavelength.

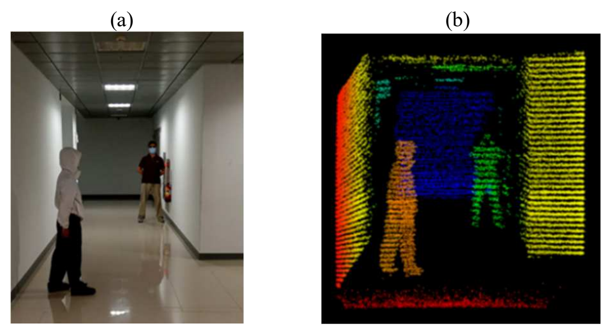

Fig. 4. (a) RGB image and the corresponding (b) PCL image.

IV. SUMMARY

In this work, we demonstrate a GeSi APD with ultralow dark currents. The corresponding dark current densities are 12.7 μA/cm^2 and 127 μA/cm^2 at unity gain and gain of 10, which are among the lowest values ever reported in the literature, and open up the possibility of adopting the GeSi APD for a wide range of applications including TOF based LiDAR.

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