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Towards Integrated Single Photon Avalanche Detectors for Visible Light (Invited)

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Abstract. Integrated avalanche photodetectors (APDs) are essential and ubiquitous devices in quantum photonics applications. While free-space APDs are a mature technology, the development of integrated APDs for visible light is still in its infancy. In this invited talk, we review our work on integrated photodetectors – the Germanium photodetector for O band, and the first integrated silicon (Si) APD for visible light. A unique feature of the integrated Si APD system for visible light is the end-fire coupling between the silicon nitride (SiN) waveguide and the Si APD in the same layer. This allows for broadband and high-efficiency coupling of light from the SiN waveguide to the Si APD for light detection, without the drawbacks of conventional interlayer coupling. Our work on integrated Si APDs based on Geiger-mode and our progress towards achieving single photon detection for visible light is discussed in the talk.

1 Introduction

Photodetectors (PDs) are indispensable components of photonic integrated circuits. Various types of PDs designs, such as PIN [1] and avalanche photodetectors (APDs) [2], have been realized on different material platforms, including III–V semiconductors, germanium (Ge), and silicon (Si). For silicon photonics, the common material for PDs is Ge [1, 2]. These are typically designed for optical communication networks that use infrared wavelengths of 1310nm and 1550nm. Integrated silicon APDs have also been demonstrated for short-reach data communications at wavelength of 850nm [3, 4]. However, it is a challenge to realize integrated silicon APDs for visible light. Recently, our group demonstrated the first waveguide-coupled silicon APDs for visible light [5]. This can be used for quantum photonics and other visible light applications. In this invited talk, we review our work on integrated PDs – the Ge PDs for O band [1], and the integrated silicon APD for visible light [5]. Our work [6] and progress towards achieving on-chip single photon detection using silicon APD in the Geiger mode is discussed in the talk.

2 Germanium Photodetectors

Our germanium (Ge) photodetector is based on a P-I-N junction design that consists of p-doped Si slab and n++ Ge, with an intrinsic Ge region for light absorption.

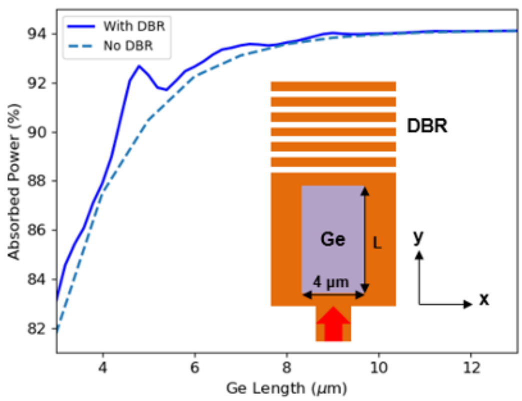

Fig. 1. Absorption of the Ge PD at different lengths. The inclusion of distributed Bragg reflector (DBR) at the exit of the Ge PD enhances the absorption.

To establish ohmic contacts, p++ Si is used. The height of the Si slab height is 220nm, while the thickness of the Ge layer is 500nm. Details regarding the design can be found in our published work [1].

An important design parameter is the absorption length of the Ge PDs. We used 3D finite-difference time-domain (FDTD) simulation to determine the fraction of absorbed power as a function of Ge length at a width of 4µm. As seen in the dotted graph of Fig. 1, the absorption saturates to 94% for length L above 8µm. For short PD with L below 7µm, the absorption is lower than 90%.

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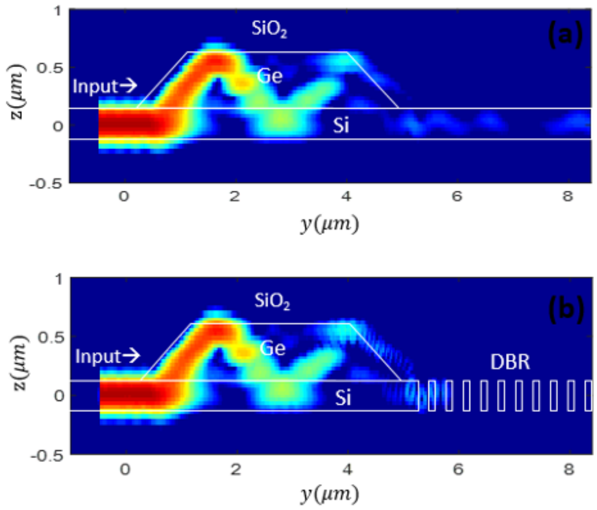

Fig. 2. Simulated electric field distribution in the Ge PD without DBR in **(a)** and with DBR in **(b)**. The use of DBR reflects the unabsorbed light back into the Ge PD for re-absorption.

It is advantageous to use PD with short length for low dark current and high speed. Distributed Bragg reflector (DBR) was therefore placed at the output of the Ge detector. The DBR has a period of 340nm and 50% duty cycle. An additional 3% of absorption was observed for short Ge length of 4.8µm. The use of DBR reflects the unabsorbed light back into the Ge PDs for re-absorption. This phenomenon is illustrated in Fig. 2.

Ge PDs of lengths L = {4.8, 6.8, 11, 17} µm at varying widths W = {4, 4.5, 5, 5.5} µm were fabricated and measured for responsivity, dark current, and O-E 3dB bandwidth performances. DBRs are included in the Ge PDs with length of 4.8µm and 6.8µm. At -2V, dark current below 4nA, responsivity of 0.87A/W, and device bandwidth of 35GHz were observed.

3. Silicon Avalanche Photodetectors

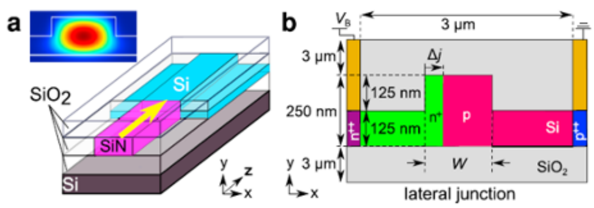

Fig. 3. The on-chip silicon APD designed for visible light. An end-fire coupling scheme in **(a)** is used to couple the input SiN waveguide with the Si rib waveguide that is n+ and p doped to form an integrated silicon photodetector in **(b)**.

Recently, our group designed and experimentally demonstrated the first monolithically integrated silicon avalanche photodetector for visible light [5]. The device structure and doping profile of the proposed on-chip silicon APD are shown in Figure. 3. A unique feature is the end-fire coupling between the SiN waveguide and the doped Si rib waveguide in the same layer. This is a straightforward design approach, but difficult for fabrication as both the SiN and Si waveguides are on the same layer. Using 3D FDTD simulation, we analysed the fraction of absorbed power by the Si rib waveguide when visible light is end-fire coupled from the SiN waveguide. In the simulation, both SiN and Si waveguides have the same width W, and a length of 10µm is used for the Si rib waveguide. At visible wavelengths around 680nm, the absorption is above 70% for W above 400nm, as shown in Fig. 4.

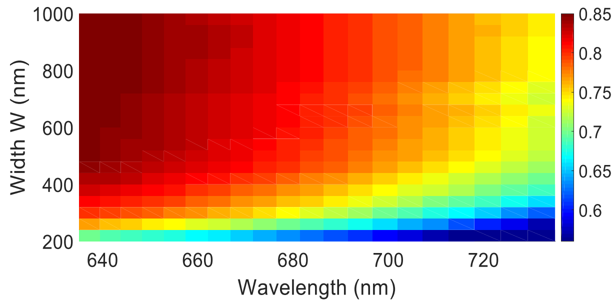

Fig. 4. The fraction of absorbed power by the Si rib waveguide of length 10µm with width W when light is end-fire coupled from the SiN waveguide with width W.

To achieve Si PDs with high absorption, we used W = {750, 900} nm for our fabrication of Si APD based on the end-fire coupling scheme. Two different designs of PN junctions were used on the Si rib waveguide – the lateral and interdigitated PN junctions. Details of the device design, fabrication, and measured results can be found in our work in [5]. A high gain-bandwidth product of 234 ± 25GHz at 20V reverse bias was demonstrated at wavelength 685nm, with low dark current of 0.12µA, and open eye diagrams at up to 56Gbps.

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