Silicon Photonics' based Single Photon Avalanche Detectors for Quantum PICs

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Abstract

Superconducting single-photon detectors have progressed massively over the last decades, however their key limitation remains: they operate in cryogenic conditions. This heavily affects the feasibility of on-chip integration, excluding the possibility of having active components alongside them. Photonic integrated circuits (PICs) for quantum information constitute the obvious example of applications suffering from this bottleneck[1]. Meanwhile, single photon avalanche diodes (SPADs) have been commonplace for decades in applications such as but not exclusively quantum optics. However, they have not drawn much attention in the integrated photonics community except for some key demonstrations of Ge-SPADs[2]. We report a novel waveguide-integrated SPAD fabricated in a Si-photonics platform (iSiPP50G). Room temperature photon detection efficiency (PDE) and dark-count rates (DCR) are characterized in a gated Geiger mode, revealing an optimistic window to the future of non-cryogenic PICs for quantum information. A 5% PDE is achieved at the wavelength of 517 nm, while resorting to vertical fiber-coupling. Whilst this method is theoretically limiting the coupling to a maximum of 9%, optical modeling reveals hybrid integration possibly unlocking coupling efficiencies above 90%, with the PDE potentially following in suit. Further modeling reveals pathways towards even higher PDEs (> 80%) and lower DCRs through junction engineering.

Introduction

The ability to detect and control individual photons plays a crucial role in quantum optics. Recent advancements in integrated photonics platforms have facilitated on-chip quantum operations, thanks to the availability of mature, low-loss materials such as silicon on insulator (SOI), silicon nitride (SiN), and III-V materials like gallium arsenide (GaAs). Hybrid integration unlocks the combination of these materials [3].

For on-chip detection of single photons, superconducting nanowire single-photon detectors (SNSPDs) have gained widespread recognition [4,5]. These detectors excel in key performance metrics for single-photon detection, achieving photon-detection efficiencies (PDE) surpassing 90%, dark count rates (DCRs) below 0.01 Hz, timing jitters below 2.6 ps full width at half maximum (FWHM), and dead times compatible with GHz count rates. However, it's worth noting that currently available SNSPDs do not integrate all these qualities into a single device [6]. One notable drawback of SNSPDs is their requirement for cryogenic temperatures below their critical superconducting threshold. The maintenance of such cryostats is intricate, energy-intensive, and expensive, thereby limiting the scalability of these platforms, particularly when incorporating power-dissipating components.

Upon reviewing the range of single-photon-sensitive technologies and acknowledging the current limitations of superconducting nanowire single-photon detectors (SNSPDs), single-photon avalanche detectors (SPADs) emerge as a potential solution to the challenges at hand. SPADs have played a significant role in quantum photonics since the early 2000s, primarily due to their capability to operate at or near room temperature. Beyond quantum photonic applications, these semiconductor-based devices have found utility in diverse fields, including LIDAR, point-of-care diagnosis, and more [7,8].
Operated in the Geiger mode, SPADs are biased beyond the breakdown voltage within a metastable regime. This characteristic enables the detector's high sensitivity, as a single carrier generation event can trigger a macroscopic avalanche. While previous developments have primarily focused on free-space applications, waveguide-integrated variants have been limited to infrared wavelengths [2]. A significant gap exists in addressing relevant quantum systems, such as diamond color centers [9], where the visible spectrum is crucial, and efficient Si-based SPADs could fill this void.
Our objective is to explore the integration of SPADs into silicon photonics platforms, positioning them as promising candidates for robust, integrated single-photon detectors. This endeavor aims to bridge the existing gap and extend the applicability of SPADs to quantum systems operating in the visible spectrum, further enhancing their versatility and impact in the field of integrated photonics.

Method

A planar P/N diode fabricated in imec's isipp50g platform is tested in the Geiger operation mode. We measure the dark count rate and the detection efficiency as a function of the applied over-bias.
The SPAD schematic cross-section shown in figure 1(a) is designed with its heterogeneous integration with a nanophotonic waveguides in mind. This micro-transfer printing method was indeed previously demonstrated to be an attractive method of integrating Si photodiodes on a complementary silicon nitride platform [13]. In this study, we employ a diode configuration featuring fibered top illumination, omitting the presence of an evanescently coupled SiN waveguide. While this choice imposes limitations on the efficiency ceiling of the detector, it remains suitable for targeted characterization and demonstrating Geiger operation in nanophotonic SPADs.
It is essential to note that the chosen illumination strategy is not optimized for efficient detection due to the limited propagation depth (sub-micrometer) and poor overlap between the focal spot and the junction. Nevertheless, measuring efficiency is crucial for positioning the point of interest on the efficiency vs over-bias curve. We view this metric as independent of optical performance, instead being connected to the field-dependent avalanche triggering probability.
Characterization is performed in a dark enclosure both with and without the presence of a synchronized train of sub-ns attenuated optical pulses. This optical train is focused on a nominal 2.5 μm spot on the diode via a lensed fiber. The response of the SPAD is read on a real time oscilloscope and the traces recorded. The avalanche pulses show voltages exceeding 50~mV, making them easily discernible from any transient spikes resulting from the off-state diode's capacitance facing the AC pulse. This 50 mV value was set as the threshold for determining the presence of an avalanche event in the data processing.

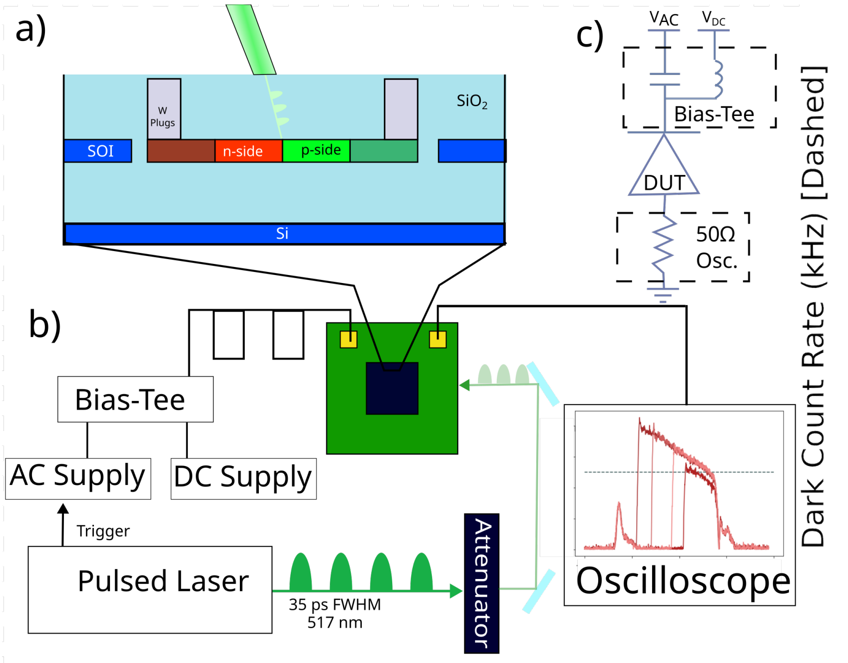

Figure 1: Schematic representation of the experimental setup: (a) Geometry of the P/N diode and coupling of the single-photon train by a lensed fiber, (b) measurement setup, (c) circuit diagram of the assembly.

Results

We present the initial attempt to operate a P/N diode on a silicon photonics platform in a gated Geiger mode. The characterization results are outlined in Figure 2. The primary limiting factor for our device is the noise figure, with dark count rates (DCRs) ranging between 10 and 100 MHz at room temperature. The device was designed using the standard body doping options provided by the imec isip50G platform, resulting in a higher-than-desired doping concentration. This elevated doping level is identified as the primary contributor to the high noise figure, as indicated by the modeling detailed in the methodology section.

The disparity between the simulated and experimental results may be attributed to trap states in the SiO2/Si interface, which were not considered in our model. The intense doping profile leads to significant field-enhanced and band-to-band tunneling carrier generation figures. It is noteworthy that no Zener diode behavior was observed in these devices, suggesting that the doping level is low enough to prevent tunneling before reaching the avalanche regime. The dark count rate recorded at room temperature is expected to decrease logarithmically with the aid of thermoelectric cooling.

On the other side of the coin, the detection efficiency reaches 5% with the aforementioned top illumination scenario. Taking into account the thickness of the SOI layer where the SPAD (220 nm) is built upon, an ideal case scenario would peak at 9% absorption efficiency. The SPAD thus shows a favourable avalanche triggering efficiency of 55.6 %. Finally, a first estimate of the global jitter (inset of figure 2) indicates it lesser than 160 ps (FWHM) which is an indication that these devices are suited for low jitter applications.

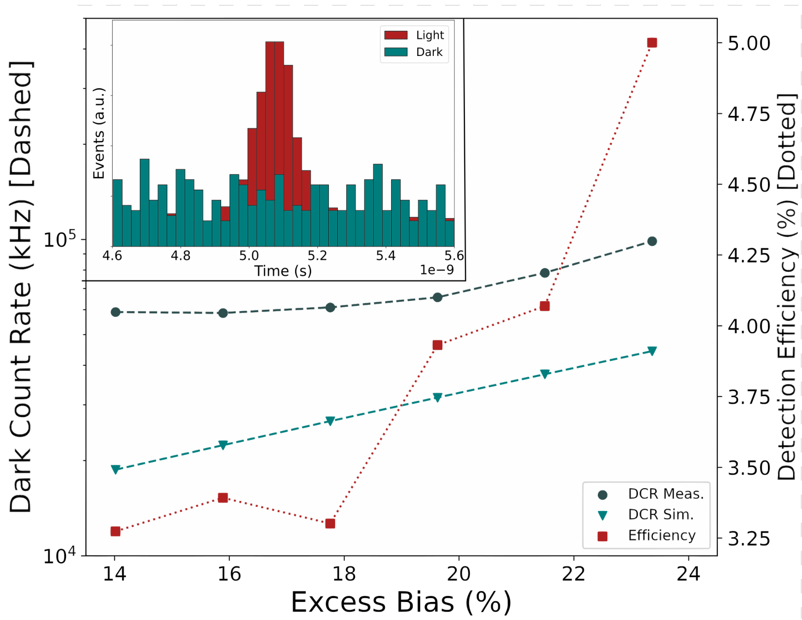

Figure 2: Summary of experimental results. The detection efficiency and dark count rates for different excess biases are shown. The breakdown bias is measured at 10.7 V. Shown in the inset plot is the histogram for the dark and illuminated acquisitions, highlighting the photon arrival time.

Conclusion

A positive outlook on the future of waveguide-integrated single photon avalanche detectors is embraced. Efficient detection was achieved by coupling visible light from an overhead fiber to the junction of a planar diode, even under perpendicular incidence. In essence, the findings reported herein underscore the promising potential of waveguide-SPADs for integrated photonics. There is substantial work ahead, involving co-optimization of design and fabrication within the scope of doping architectures and the realization of hybrid integration. Nonetheless, waveguide-integrated Si-SPADs emerge as a viable, CMOS-compatible, and temperature-robust alternative, signaling a bright future for the field.

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