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A Review of Ge-on-Si Single Photon Avalanche Diode (SPAD) Photodetectors and Applications

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1. Introduction

CMOS single photon avalanche diode (SPAD) photodetectors are now a mature technology being used for a wide range of applications including range-finding for autonomous vacuum cleaners, facial recognition, medical imaging and prototype automotive lidar systems [1]. A SPAD consists of an absorber which generates electron-hole pairs and an avalanche gain region which amplifies the single photon into a current sufficient to be detected by electronics. SPADs are operated above the breakdown voltage of the avalanche region, in Geiger mode operation, where a single photo-generated carrier produces almost instantaneously a large multiplied current through impact ionization.

The use of Si as the absorber limits absorption of photons to ≤ 1 µm wavelength but many applications including fibre-optic based telecoms, quantum communications over fibre and range-finding / lidar over large distances (> 200 m) and/or through obscurants require longer wavelengths. InGaAs/InP SPADs operating out to ~1.7 µm wavelength have been commercially available for over a decade but at present only single pixel detectors are commercially available at significant cost (>£10k) and single photon detection efficiencies (SPDEs) of ≤ 35% are well below CMOS SPAD efficiencies in the visible region.

By added Ge heterolayers onto Si, photons can be absorbed out to ~1.7 µm wavelength enabling SPADs to be produced operating at the important short-wave infrared (SWIR) wavelengths of 1310 and 1550 nm. This review will detail some of the key steps in producing the first Ge-on-Si SPADs [2] with useful single photon detection efficiencies (SPDEs) [3][4], explain the present performance, discuss options to improve the future performance [5][6][7] and discuss requirements for key markets and applications [8].

2. Key Design Principles

All Ge avalanche photodetectors (APDs) have demonstrated photon counting applications for many years but were limited to low temperature operation due to high dark count rates (DCR) when operated in Geiger mode [9]. Si is one of the best avalanche gain materials and the indirect bandgap with a significantly larger direct gap results in efficient, low-noise avalanche multiplication [3]. Therefore the addition of SiGe or Ge as an absorber on top of a Si avalanche region in a so-called separate absorber and charge multiplication (SACM) device is the preferred approach for high performance SPADs [6].

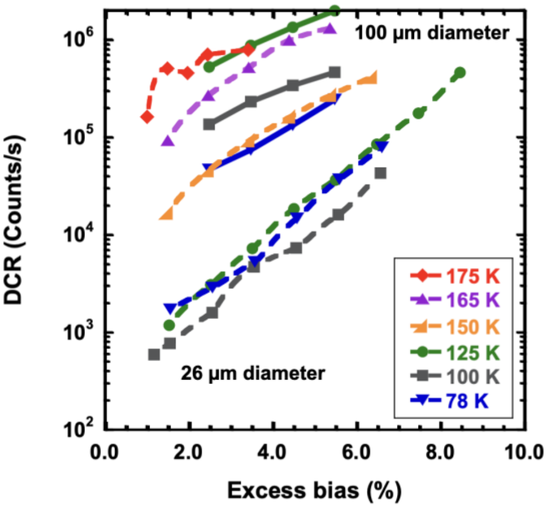

Fig. 1: The DCR as a function of temperature for 100 µm diameter (solid lines) and 26 µm diameter (dashed line) Ge-on-Si SPADs [3][4].

3. SPAD Performance

The first Ge-on-Si SPAD devices were mesa etched of 25 µm diameter and demonstrated 4% SPDE at 1310 nm when operated at 100 K with a large DCR of 6 mega-counts per second (cps) [2]. These devices were also the first SPADs to demonstrate operation at 1550 nm on a Si substrate with the indirect bandgap absorption producing 0.15% SPDE [2].

A step change in performance was obtained by moving to a planar process [3]. By locally defining the p^{++} top contact well away from any etched sidewalls, the DCR could be reduced by a factor of 40 for devices with equivalent diameters ([4] and Fig. 1). This demonstrated the importance of sidewall traps in the device performance and allowed SPDEs up to 38% at 125 K [3] (Fig. 2). A clear benefit of Group IV SPADs compared to III-V devices is reduced afterpulsing:

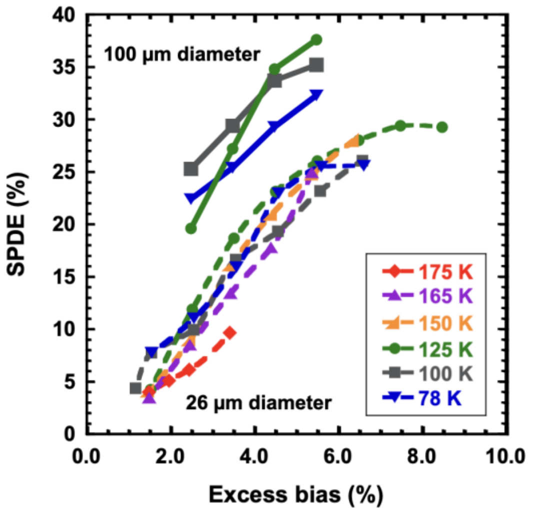

Fig. 2: The SPDE as a function of temperature for 100 µm diameter (solid lines) and 26 µm diameter (dashed line) Ge-on-Si SPADs [3][4].

where carriers are trapped in the avalanche region and then released at a later time. It is afterpulsing that determines the repetition rate for most applications as SPADs require long hold off times to reduce afterpulsing probabilities to a negligible level. Initial afterpulsing measurements on Ge on Si SPADs have demonstrated at least a factor of 5 reduction in afterpulsing compared to InGaAs/InP SPADs under identical operating conditions [3].

5. Comparison of SWIR SPAD Technologies

Fig. 3 compares the noise equivalent power (NEP) from the best planar Ge-on-Si SPADs with 26 µm [4] and 100 µm diameters [3] with a range of commercial InGaAs/InP SPADs and other devices [7][9][10] at 1310 nm wavelength. It is clear that signficant progress has been made with planar Ge-on-Si SPADs but further progress is required to get to the performance of InGaAs/InP SPADs at 223 K.

4. Routes to Improving SPAD Performance

All InGaAs/InP SPADs are typically run on Peltier coolers at ≥ 223 K. To date the highest operating temperature of Ge-on-Si SPADs is 175 K [4] with clear single photon detection but the DCRs at these temperatures are still high compared to III-V devices and DCR increases exponentially with increasing temperatures [6][7]. Simulations are starting to provide evidence that there are still hot spots in these planar SPAD devices which dominate the generation of DCR. It is also clear that high quality surface passivation of the deep trench isolation is essential to reducing DCR and improving the operating temperature. The present Ge-on-Si SPAD results have 1 µm of Ge which only absorbs ~50% of the photons so extending the thickness of Ge should increase SPDE and higher temperature operation will improve SPDE at longer wavelengths. Also the initial afterpulsing results suggested that threading dislocations from the Ge-Si heterointerface that thread down into the Si may dominate the afterpulsing so reducing these should allow afterpulsing values similar to those demonstrated in CMOS SPADs.

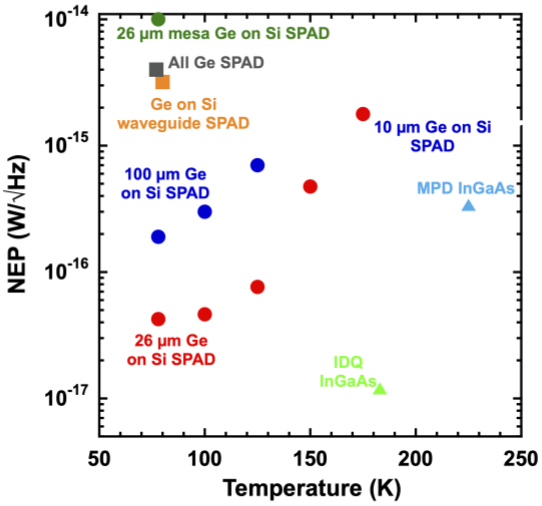

Fig. 3: The NEP as a function of temperature for a range of all Ge, Ge-on-Si and InGaAs/InP SPADs at 1310 nm [2][3][4][7][9][10].

6. Conclusions

Ge-on-Si SPADs have the potential to allow far cheaper SWIR SPAD devices for a range of applications including telecoms, quantum comms., rangefinding and lidar. Already initial lidar results with Ge-on-Si SPADs have demonstrated the potential for rangefinding over 1 km with eye safe laser powers [8]. These are still early devices from an immature technology with significant potential to optimise the future performance. Simulations suggest that far higher SPDE than III-V SPADs should be achievable due to the better band-structure [4] but DCR may always be poorer [7]. The lower afterpulsing from Ge-on-Si devices may allow higher measurement repetition rates than III-V SPADs and is key for most applications.

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