Ge-on-Si Single Photon Avalanche Diode Detectors for LIDAR in the Short Wave Infrared

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Abstract: A planar geometry Ge-on-Si single photon avalanche diode detector, is used to demonstrate light detection and ranging (LIDAR) in laboratory conditions. Modelling demonstrates that kilometer range-finding at 1450 nm is achievable with eye-safe laser powers. Afterpulsing is found to be approximately 20 % that of commercial InGaAs/InP devices, demonstrating potential for increased repitition rates.

1. Introduction

Single photon avalanche diode (SPAD) detectors are reverse biased diodes biased above breakdown, such that a single photon can cause a self-sustaining avalanche current, detectable with picosecond timing precsion. Such devices are of significant interest for time-of-flight LIDAR applications; a technology that will be key for self-driving cars or autonomous vehicles (AVs). The majority of AV LIDAR systems are based on Si detectors, which are low-cost but are limited to operation at wavelengths <1000 nm. There are numerous benefits for LIDAR using short wave infrared (SWIR) wavelengths, including approximately a 20 times increase in eye-safe laser powers, reduced solar background radiation, and increased penetration through fog and smoke. InGaAs/InP devices are state-of-the-art for SWIR SPADs, however this technology is prohibitively expensive for mass market applications and suffers from afterpulsing. Here, we demonstrate that Ge-on-Si devices operating in the SWIR are suitable for LIDAR applications, using a material platform that is relatively low-cost compared to InGaAs/InP devices due to compatability with Si foundries.

2. Experiment and Results

Novel planar geometry Ge-on-Si SPADs were recently demonstrated [], with record high single photon detection efficiencies (SPDEs) of 38 % at 1310 nm wavelength, at temperatures of 125 K. Significantly reduced dark count rates (DCR) were found compared to prior Ge-on-Si SPADs [**?**], and record low noise-equivalent powers of 1.9×10^{-16}W/Hz$^{0.5}$ were measured; a 50-fold improvement on the prior-art. This was achieved by confining the electric field of the device away from etched sidewalls with a locally implanted Boron charge-sheet region, as shown by finite element modelling in Fig. 1a). A charge-sheet is required in separate absorption and multiplication structures to mediate the electric field between the Ge absorber and the Si avalanche region, however in previous Ge-on-Si devices the charge sheet was in-situ doped and an etch was used to define the active device area. This can lead to electric field hot-spots, and interaction with generation-recombination centres on etched sidewalls, both of which are reduced with the planar design. Afterpulsing is another key performance metric for SPADs, which is the triggering of a device due to charge released from traps that were filled from a prior trigger. This is a significant issue for InGaAs/InP devices due to defect densities in the InP avalanche layer, which means that a hold-off time is required between photo-detection events, to allow traps to empty. Afterpulsing was measured using a 100 μm diameter Ge-on-Si device using a dual gate technique [], and compared to a commercial InGaAs/InP devices operated in nominally identical conditions. As demonstrated in Fig. 1b), it was found that with 10 μs hold-off time, the Ge device has a probability of afterpulsing that is 20 % that of the commercial InGaAs device, due to the reduced defect density in the Si avalanche region compared to InP. This reduced afterpulsing translates to higher repetition rates in real-life systems, which could be key to LIDAR application in terms of reducing acquisition times.

A 100 μm diameter single pixel Ge-on-Si SPAD was used to demonstrate LIDAR imaging of a model bus in laboratory conditions. The device was operated at 100 K and arranged in a mono-static transceiver configuration for imaging the model at a distance of 0.4 m. A 1450 nm wavelength laser pulsed at 104 kHz was used with an average power of 912 pW. At each pixel, a number of repetitions are made in an electrically gated time-correlated single photon measurement, generating a timing histogram of detection events. The object is scanned using a motorised stage to generate images. A pixel-wise algorithm described in [] was used to extract both intensity and depth maps, with crops shown in Fig. 1c). The model bus can be excellently resolved with per-pixel averaging of 10 ms, with clear resolution of the depth in the window areas and on sloped sections. Based on the SPAD performance metrics (SPDE of 15 % at 1450 nm, and DCR of 2.6 k counts/s at 100 K), the maximum range for a LIDAR measurement can be predicted based on a modified LIDAR equation for Geiger-mode operation []. The maximum range of detection was be calculated for various averaging times, assuming conservative estimations for object reflectively (10 %) and internal system losses (10 dB). As shown in Fig 1d), 1 km range-finding is achievable with eye-safe power levels and 3 ms averaging, in the absence of atmospheric obscurants, which is highly encouraging for Ge-on-Si devices.

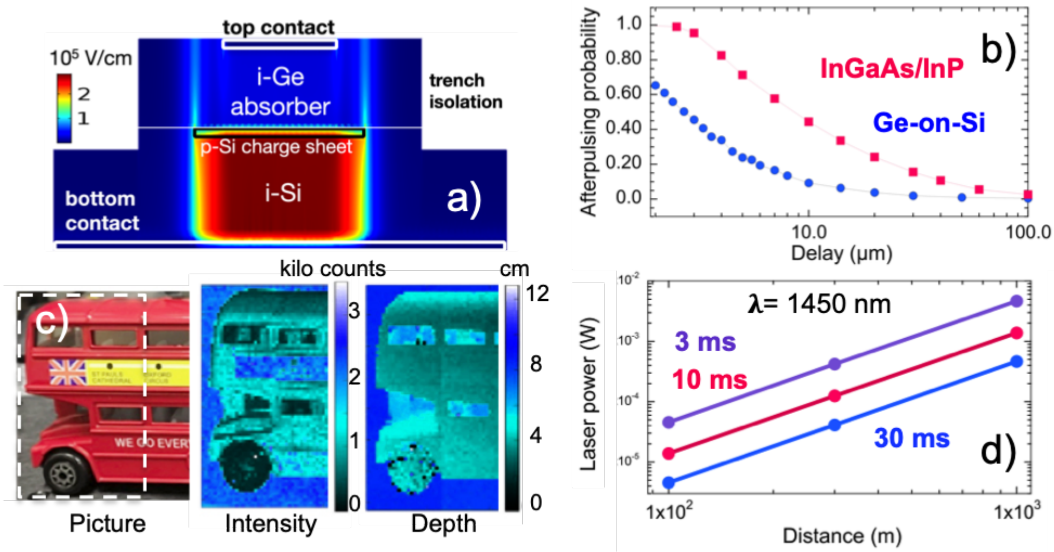

Fig. 1. a) Finite element model of a planar geometery Ge-on-Si SPAD. b) Afterpulsing probability of a 100 μm diameter Ge-on-Si SPAD and a commercial InGaAs/InP SPAD. c) Image of toy bus and asociated intensity and depth maps from LIDAR measurement. d) Calculated range vs laser power for a range of integration times at λ = 1450 nm.

3. Conclusion

Planar geometry Ge-on-Si devices were developed with high SPDE of 38 % at 1310 nm wavelength, at 125 K. Afterpulsing measurements were taken and compared to commercial InGaAs/InP devices, and it was shown that the afterpulsing probability in our devices is $\sim$ 20 % that of commerical InGaAs/InP devices at 10 μs hold off times, therefore allowing for higher repetition rates. LIDAR imaging was demonstrated in laboratory conditions using a single pixel Ge-on-Si SPAD, and a modified LIDAR equation was used to estimate device performance in real-world range-finding. It was found that km-rangefinding is achievable with our Ge-on-Si devices in the SWIR (1450 nm) at eye-safe laser powers, with integration times of 3 ms. The results are hugely encouraging for future low-cost LIDAR applications in the SWIR. Future work will focused on device optimisation to allow an increased temperature of operation, and higher absorption at 1550 nm.

References