Si and Ge-on-Si self-assembled micro-crystal SPADs

Fabio Signorelli[1], Andrea Barzaghi[2], Virginia Falcone[2], Joao Valente[3], Roberto Bergamaschini[4], Franco Zappa[1], Douglas J. Paul[3], Giovanni Isella[2], Alberto Tosi[1]

[1]*Dipartimento di Elettronica, Informazione e Bioingegneria, Politecnico di Milano, 20133 Milano, Italy*

[2]*L-NESS Dipartimento di Fisica, Politecnico di Milano, 22100 Como, Italy*

[3]*James Watt School of Engineering, University of Glasgow, Glasgow G12 8LT, United Kingdom*

[4]*L-NESS Dipartimento di Scienza dei Materiali, Università di Milano-Bicocca, 20125 Milano, Italy*

Quantum optics applications, such as quantum key distribution (QKD), require high-speed single-photon detectors for the shortwave infrared (SWIR) range. Currently, InGaAs/InP single-photon avalanche diodes (SPADs) are the preferred solution when compact and reliable systems are needed, but they have limited maximum count rate (due to afterpulsing) and they cannot be integrated with standard CMOS circuits. As an alternative, Ge-on-Si SPADs benefit from the good absorption properties of Ge in the SWIR range and can be integrated onto a CMOS-compatible silicon substrate, thus achieving cost-effective solutions and enabling the wide deployment of QKD systems for securing a large number of communication links in metropolitan area networks operating at 1310 nm. Additionally, Ge-on-Si SPADs feature low afterpulsing, thus higher secret key generation rates can be obtained. However, state-of-the-art Ge-on-Si SPADs show a high dark count rate (DCR) also at low temperatures, because of the dislocations generated by conventional Ge/Si epitaxy [1].

Here, we present a novel technological platform, based on vertical hetero-epitaxy (VHE) of Si and Ge micro-crystals, which enables the fabrication of SPADs and solid-state photomultipliers (SSPMs) with high photon detection probability (PDP) and high fill-factor (see Fig. 1a). Thanks to the innovative VHE approach, the dislocations generating at Ge/Si interface are expelled towards the lateral surfaces of the micro-crystal, thus enabling the fabrication of low-DCR micro-crystal-based SPADs (or microSPADs) [2].

As a first step, we modeled an all-silicon microSPAD with a thick (> 10 µm) absorption region, estimating a PDP > 75% in the visible range thanks to intrinsic light focusing and field confinement effects of micro-crystals. We fabricated a proof-of-concept prototype with a thinner (~ 3 µm) absorption region and a boron-implanted p$^+$ anode contact to better confine the high electric field at the center of the device, demonstrating for the first time Geiger-mode operation of microSPADs. Despite the measured DCR is quite high, further improvements of the fabrication process (e.g., annealing steps and dedicated passivation) will improve it, by reducing the concentration of generation-recombination centers close to the lateral surfaces.

Concerning Ge-on-Si microSPADs, Fig. 1b shows the optical and electrical design of a first device that will be soon fabricated. The absorption probability was estimated by means of finite-difference time-domain (FDTD) optical simulations, while avalanche triggering probability is calculated both inside and outside the multiplication region, by taking into account the diffusion of minority carriers towards the high-field region. We estimated the PDP of the Ge-on-Si microSPAD (see Fig. 1c) and, despite the depleted Ge layer is only 0.5 µm-thick, we expect more than 50% PDP at 1310 nm.

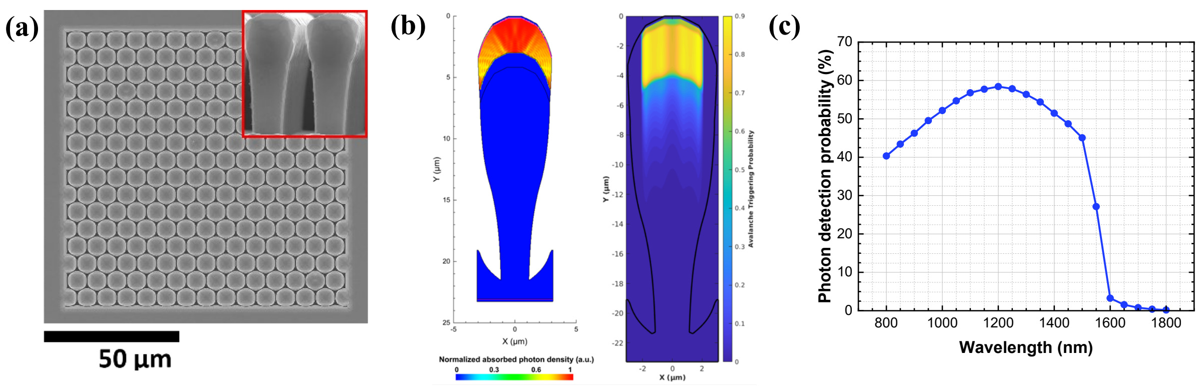

Fig. 1 (a) SEM image of micro-crystals grown on a patterned region. The inset shows a lateral view of two micro-crystals. (b) FDTD optical simulation at 1550 nm wavelength (left) and avalanche triggering probability distribution (right) of the designed Ge-on-Si microSPAD. (c) Estimated PDP at different wavelengths of the proposed Ge-on-Si microSPAD.

References

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