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Designing Silicon-Germanium Photodetectors with Numerical Optimization: The Tradeoff Between Quantum Efficiency & Phase Noise

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With its compatibility for monolithic integration with silicon and its higher electron and hole mobilities compared to silicon, germanium is an essential semiconductor to be used in photonic devices—including photodetectors. To determine the stability, efficiency, and speed of a photodetector, one must measure or calculate the phase noise, quantum efficiency, and response time of the photodetector. We recently developed an efficient drift-diffusion equations solver that uses a non-uniform time-stepping [1] and both single-frequency and broadband excitations to calculate the phase noise [2], quantum efficiency [2], and bandwidth [3] of photodetectors that have several layers of semiconducting materials with varying thicknesses and doping concentrations.

Designing a high-performance photodetector or even improving the performance of an already existing design is a challenging task due to the required computation time, difficulties in estimating the sensitivity of the device to the design parameters, and the existence of design constraints. In this work, we first study the Si-Ge photodetector proposed in [4], shown in Fig. 1 (a). The 0.6-μm Ge layer has a doping density that is graded from 5×10^{19} cm^{-3} to 2×10^{17} cm^{-3}. Fig. 1(b) shows the good agreement between the measurement [4] and our numerical results for the RF output power of the photodetector under the reverse bias of 5 V.

We use three different numerical optimization methods (NOMs): genetic algorithm (GA), surrogate algorithm (SA), and particle swarm optimization (PSO) algorithm to design photodetectors with a higher quantum efficiency and a lower phase noise. The thicknesses and gradient doping concentrations of each layer (n Ge, n Si, and $n+$ Si) are left to be determined by the NOMs. In Fig. 1 (c), blue, red, and orange circles represent the phase noise vs. quantum efficiency of the 1828 Si-Ge photodetectors designed by GA, SA, and PSO methods, respectively. All methods are able to design photodetectors with a much higher quantum efficiency ($\sim$0.18 vs. 0.12) and a lower phase noise (-180 dBc/Hz vs. -168 dBc/Hz). However, we observe two distinct trends. The first trend, highlighted with a transparent yellow line, shows a linear relationship between the highest quantum efficiency achievable at a desired phase noise (or vice versa). The second trend, highlighted with the green transparent curve, shows the trend typically observed in optimization studies where there is a trade-off between two parameters. The intersection of the yellow line and green curve shows the numerical limit of the highest achievable quantum efficiency with a moderately low phase noise level. In Fig. 1(d), we plot the electric field distribution for one of the high-performing designs that has a quantum efficiency of 0.18 and a phase noise of -180 dBc/Hz, where the orange curve shows the doping concentration distribution along the photodetector. Gradient (decreasing) doping density levels in the absorber and collection layers improves the quantum efficiency by increasing the width of the depletion region and suppressing the Auger mechanism. A detailed analysis of the optimized designs and how the performance of NOMs change with increasing layer number will be discussed at the conference.

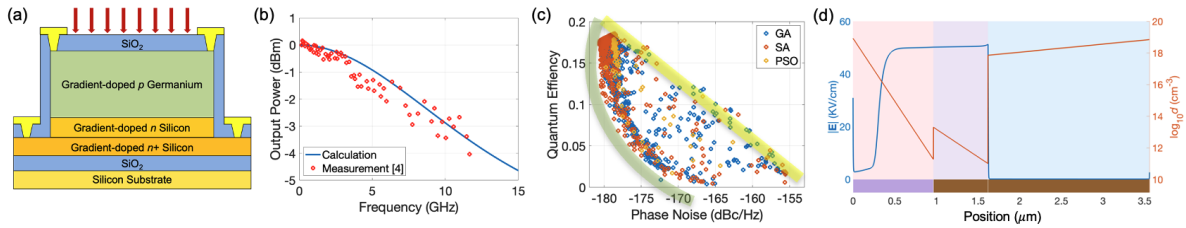

Fig. 1: (a) Schematic view of the silicon-germanium (Si-Ge) photodetector cross-section with p Ge, n Si, and $n+$ Si layers. (b) RF output power vs. frequency. (c) Blue, red, and orange circles represent the phase noise and quantum efficiency of each design generated during the GA, SA, and PSO study, respectively. The transparent green curve and yellow line are included to highlight the trends. (d) Electric field (blue) and doping concentration (orange) profiles of one the of the optimized designs.

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