# Sub-fF Nanophotodetector for Efficient Waveguide Integration

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*Abstract*—**We simulate a 33% quantum efficiency, 240 aF germanium photodiode coupled directly to a silicon waveguide. The variation of geometric parameters barely degrades the performance, showing promise for future fabrication.**

***Keywords-nanophotodetector; germanium photodetector; silicon photonics***

## I. INTRODUCTION

Optical interconnects are an increasingly popular solution for reducing the power consumption of computer chips, however the full optical link must be much more power efficient than a metal wire for it to be competitive, likely below a fJ/bit[1]. In order to reduce the power consumption of an optical link, the photodetector must be extremely sensitive, allowing fewer photons to be used per bit of information. This requires a reduction in capacitance, or the physical size of the photodiode since the capacitance is proportional to the linear dimension of the photodiode.

For silicon photonics operating at 1500nm wavelength, germanium is commonly used as the detector material for both its CMOS compatibility and optical bandgap near that wavelength. However germanium is a relatively poor absorber at those wavelengths, with an absorption length of over 2 μm. An evanescently coupled waveguide photodetector has an even longer length. The current smallest reported capacitance germanium detector is simulated to be 2.4 fF, with an estimated quantum efficiency of 90% at 1500 nm[2]. Previously, an antenna-coupled photodetector has been proposed to reduce its capacitance, however, its quantum efficiency is unacceptably low[3].

In this paper, we report on a subwavelength-scale metal-clad germanium nanophotodetector with a dimension of 400nm x 400nm x 190nm. Our detailed simulation shows that an ultralow capacitance of 240aF can be achieved while maintaining a quantum efficiency of up to 34%.

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## II. METAL CLAD BOX PHOTODIODE

To enhance light absorption in a subwavelength germanium region, we encapsulate the germanium in a metal optical cavity. Previously, we have shown that a metal-clad nanolaser can be efficiently coupled to silicon photonic waveguides [4]. Similar cavity can be adopted for efficient coupling to nanophotodetectors. The absorption is enhanced by the nano-optical cavity at resonance wavelength.

The proposed nanophotodetector is shown in Fig. 1. The key components include the germanium absorption region, which forms the bulk of the optical cavity, and has dimensions which largely determine the resonance. Aluminum encapsulates the entire cavity to reduce radiation loss from the dielectric mode. Oxide cladding around the germanium reduces the metal loss by

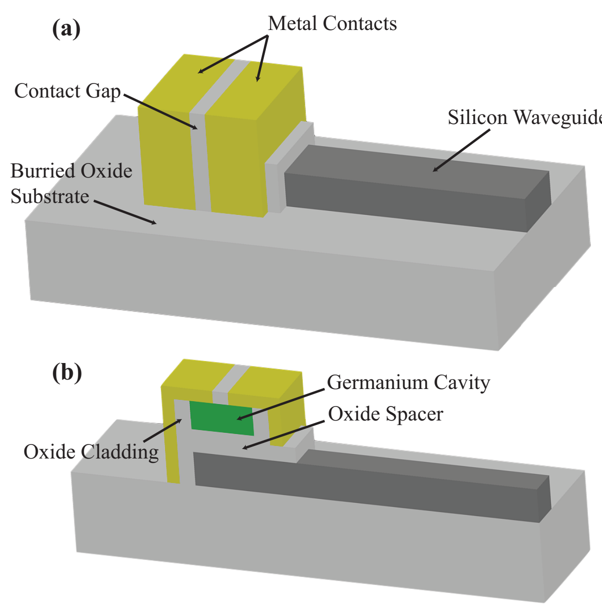


Figure 1. (a) Schematic of metal-clad nanophotodetector coupled to silicon photonic waveguide. (b) Cutaway to show the subwavelength germanium absorption region.

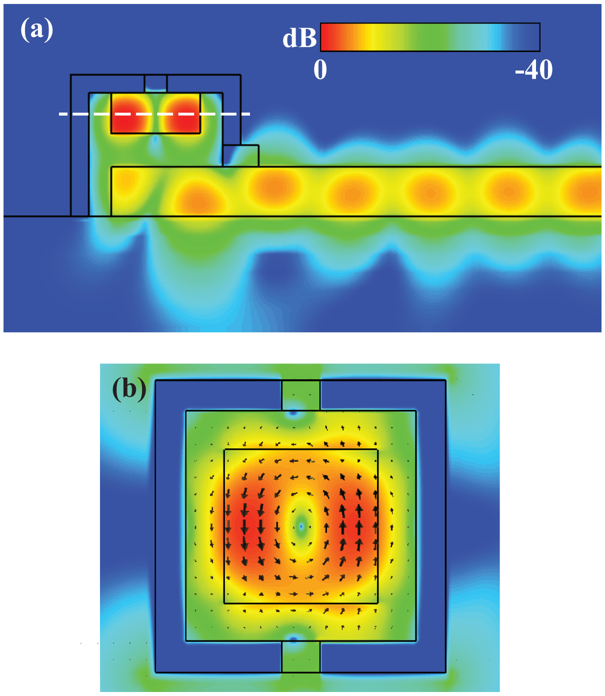


Figure 2. (a) Optical energy density along the center cross-section shows strong enhancement in the germanium cavity. (b) Optical field profile shown for the slice marked in (a) demonstrates the enhancement caused by the gap in the circular doughnut mode.

isolating the field from the metal. The oxide between the germanium cavity and silicon waveguide turns out to be critical in controlling the amount of radiation between the waveguide and cavity. While most germanium photodiodes are now grown directly on silicon[5], it is possible to obtain single crystal germanium on oxide on silicon using the rapid melt growth technique[6]. One other critical feature is the gap in the metal box, which allows for two contacts to be present. The spacing between contacts alters how well the cavity mode couples to the waveguide mode. Either a metal-semiconductor-metal (MSM) or p-i-n structure can be employed for the proposed nanophotodetector.

The results shown are from finite-difference time-domain (FDTD) simulations of the electromagnetic absorption by the germanium region using CST Microwave Studio. The mode profile shows the dielectric ‘doughnut’ mode, where the electric field rotates circularly in the substrate plane, with almost no field in the center of the cavity. Most of the energy (77%) is confined in the germanium. The gap in the metal creates an asymmetry in the electric field (Fig. 2(b)), enhancing the fields that are aligned with those of the TE mode in the waveguide. This enables us to achieve high coupling efficiency (44%) with the waveguide.

## III. Calculation of Efficiency

In order to characterize the performance of the device as a photodetector, we will assume that all carriers generated by an absorbed photon will be extracted, and so all discussions of efficiency will refer to the absorption of photons. The total efficiency is defined as a combination of coupling efficiency and internal efficiency. The coupling efficiency is calculated by exciting the resonant mode and measuring the power coupling to the waveguide with respect to the total power leaving the structure. The internal efficiency is the ratio of the power absorbed by germanium and the total absorbed power (by germanium and metal) [7]. This is calculated using quality factors by successively introducing loss into the system.

## IV. Dimensions and Performance

The length and width of the germanium cavity largely determine the resonant frequency of the mode, and are chosen to be 400 nm, which matches the width of the silicon waveguide. The thickness of the germanium is then chosen to be 190 nm to set the resonant wavelength at 1500 nm. For reference the silicon waveguide is 220 nm thick. The aluminum cap is thin, 80 nm, and the gap between the contacts is 110 nm. The oxide spacer between the germanium and silicon waveguide is 150 nm, and the oxide cladding around the germanium is 110 nm. The capacitance for these dimensions is calculated to be 240 aF, an order of magnitude less than the currently reported minimum capacitance for a waveguide integrated photodiode.

In the example shown in Fig. 2, the total efficiency is 31%, composed of a coupling efficiency of 44% and an internal efficiency of 70%. The structure is very well matched, with the total radiation quality factor ($Q_{rad}$ =28.7) very closed to quality factor due to

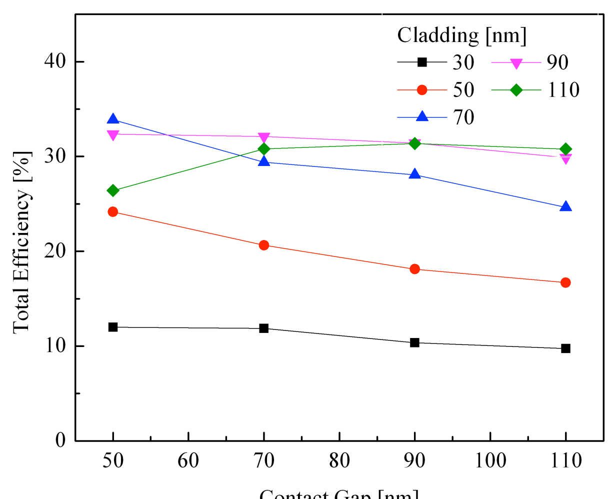


Figure 3. Total quantum efficiency of the nanophotodetector versus the gap spacing between aluminum contacts for various oxide cladding thickness.

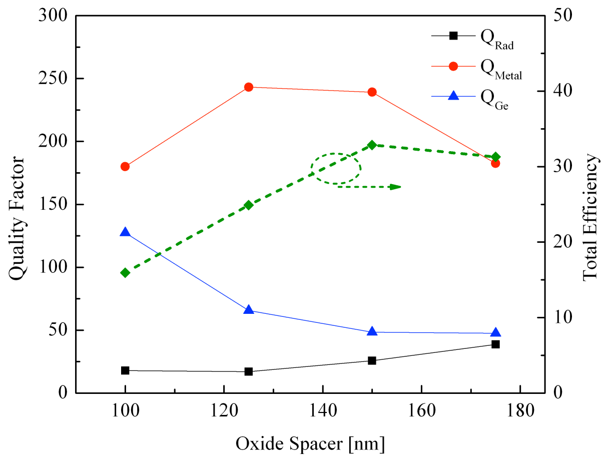


Figure 4. Quality factors showing optimization point, with total efficiency maximized.

absorption ($Q_{abs}$ =34.5). Most of the absorption is occurring in the germanium as opposed to the aluminum, since the quality factor due to absorption in germanium ($Q_{Ge}$=49.7) is much lower than that of aluminum ($Q_{Al}$ =123). It is apparent that the coupling efficiency is limiting the total efficiency of the device. The coupling efficiency may be increased by reducing the oxide thickness to its optimal point, creating critical coupling. In addition the coupling efficiency can be increased by altering the cavity thickness and cavity width to their optimum point so that the k-vector of the cavity mode very closely matches that of the waveguide mode. It should be noted aluminum is used instead of gold, which is more favorable for subwavelength cavities due to lower optical losses. However the oxide cladding effectively mitigates the metal loss, which is demonstrated by the gold clad cavity having only a slightly higher total efficiency of 41%. The tradeoff is then between a slightly higher efficiency and potential CMOS compatibility.

Shown in Fig. 3 are the results of a parameter sweep where the oxide cladding and contact spacing are varied. The cladding thickness is important because of its role in keeping the metal away from large electric fields where losses would be incurred. The contact gap is important, because the more metal overlap with the mode, the stronger the asymmetry leading to better coupling efficiency. With a cladding thickness of 90-110 nm, a wide range of contact gaps give a total efficiency of 31-33%, while with a 70nm cladding and 50 nm contact gap, the efficiency is pushed to 34%.

In Fig. 4, the oxide spacing is varied. It is clear there is an optimal value for the oxide spacing (150nm) as this largely controls the radiation between the cavity and waveguide, and obtaining critical coupling is preferred. This is demonstrated by the relative matching between absorption and radiation Q factors, while keeping the metal absorption Q as large as possible.

What the parameter study largely demonstrates is the overall insensitivity of the optical performance of the device with respect to the geometric parameters. This has very promising implications for the future fabrication of such a device. A similar study would need to be done to optimize this cavity for TM mode propagation, since the mode matching between this cavity mode and the TM waveguide mode is very poor. This is not considered a major drawback since typically the light present in a waveguide is already polarized to be either TE or TM.

## V. Conclusion

We have presented a proposed design for creating a 34% efficient Germanium photodiode coupled to a silicon waveguide. The capacitance is 240 aF, which should make the photodiode very sensitive. A parameter study was done, showing that the overall efficiency is not sensitive to the geometric parameters, implying that there is a fairly wide fabrication tolerance.

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