Self-aligned Silicon Fins in Metallic Slits as a Platform for Planar Tunable Nanoscale Resonant Photodetectors

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Abstract: We demonstrate self-aligned fabrication of etched silicon fins in metallic slits and show that this structure supports both dielectric and plasmonic resonances and photodetection that can be tuned by varying the width of the fin
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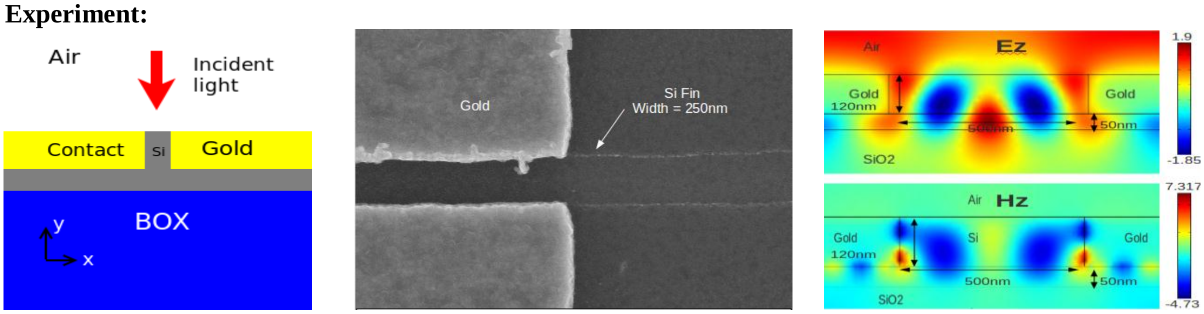
1. Motivation:

The ability to engineer tunable resonances in nanoscale structures holds great promise for various applications like detectors for future spectral systems wherein we can envision multiple resonant detectors, each sensitive to different wavelengths, while being located within one beam spot. If detectors of different wavelengths can all be fabricated lithographically within one such layered structure, such devices could be compatible with silicon CMOS fabrication techniques, possibly adding multispectral capability directly in the chip fabrication itself. In addition, since the detectors would be inherently nanoscale, they satisfy the stringent energy constraints (< 1fJ/bit received energy for on-chip operation) required for optical interconnects [1]. Other applications include compact on chip spectroscopes for biosensing and disease detection, wavelength division multiplexing, and multi-spectral imaging. Here we propose and demonstrate a novel planar approach for fabricating tunable resonators and photodetectors.

The ability of metals to confine light at the deeply subwavelength scale has long been used to realize many kinds of antenna structures for nanoscale detectors [2,3]. Metals have also been used as contacts in MSM structures [4]. One of the main ideas presented in this paper is that the same metallic structure can be used both for light confinement and carrier extraction [5]. This additional functionality leads to devices that cannot be realized by purely dielectric structures. Designing resonators that can be tuned by a lateral dimension leads to a planar, single step fabrication process which reduces the complexity and leads to high-yield devices.

2. Experiment:

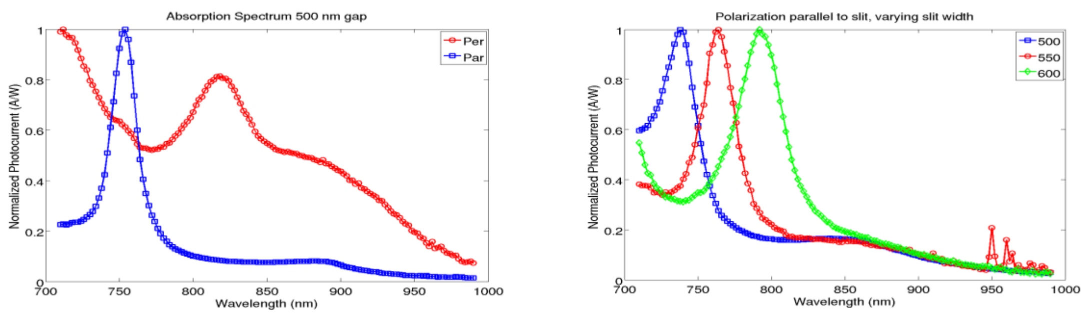


(a) (b) (c)

Figure1: (a) schematic side-view of the device, with light incident from top (b) SEM top-view image of a representative device showing the Si fin aligned to metallic slit (c) Mode profiles (FDFD) for the dielectric resonance (E_z, incident light polarized parallel to slit) and the plasmonic resonance (H_z , incident light polarized perpendicular to slit) .

Fig. 1(a) shows the schematic of our device. The device is fabricated on an SOI platform. The Si fin is defined by e-beam lithography followed by dry etching. The metal is self-aligned to the fin by metallization (Cr/Au) followed by a hard mask lift-off process. The thickness of the fin and the metal are defined independently during dry etching and metallization respectively. Fig. 1(b) shows an SEM (top view) of a representative device with Si fin width 250 nm. As can be seen, the metal is aligned precisely to the fin. With this process, we have been able to fabricate structures with fin width down to 75 nm. The two metal pads shown in the SEM serve as both antenna structures for light confinement and as contacts for carrier extraction.

Fig. 1(c) shows the field plots (calculated using Finite Difference Frequency Domain simulations) at resonance for incident polarization along the slit (E_z) and perpendicular to the slit (H_z). The slit direction is along z (out of the plane of the page in Figs. 1(a) and 1(c)). As can be seen, the structure supports resonances in both polarizations. For polarization along the slit (E_z), the structure supports a dielectric resonance with field primarily confined in the semiconductor. The metal here serves mainly to block out the background non-resonant absorption and photocurrent from the underlying silicon. For polarization perpendicular to the slit, the structure supports a plasmon resonance. In this case, the field confinement is maximized at the metal semiconductor interface as shown in the field plot for H_z.



(a) (b)

Figure 2: (a) Plot shows the measured absorption spectrum of a 500 nm width device in two perpendicular polarizations (b) Plot shows slit width dependence of measured absorption resonance wavelength for polarization parallel to the slit. (Photodetection from light leaking through a gap between the metal and semiconductor leads to a higher background non-resonant photodetection in these samples compared to (a))

Fig. 2(a) shows the normalized measured absorption spectrum of a 500 nm width device in two perpendicular polarizations. As can be seen, both polarizations show resonances at different wavelengths, which shows that the polarization response of the structure can be engineered by manipulating the geometrical properties of the system. The dielectric resonance shows higher Q. The lower Q in the plasmonic case can be attributed to the ohmic loss in the metals. For a given wavelength, the dielectric resonance shows cut-off when the width is reduced below $\lambda/2n$ but the plasmon resonance persists down to deeply subwavelength scales. Both the dielectric and plasmon resonance show strong width dependence, and can be tuned by varying the width of the structure. Fig. 2(b) shows the width dependence of the dielectric resonance (polarization along the slit). As the width is varied from 500 to 600 nm, we can see that the resonance red-shifts, which can be intuitively explained by thinking of the resonance as a whispering gallery mode that circulates in the structure in both clockwise and counter-clockwise orientation, as opposed to some simple Fabry-Perot like resonance where the resonant frequency is independent of width. This ability to tune resonance with width enables us to leverage planar processes like CMOS fabrication.

3. Conclusion:

In summary, we have demonstrated a self-aligned fabrication procedure for etched silicon fins in metallic slits leading to both dielectric and plasmonic resonances in polarizations along and perpendicular to the slit and spectrally tunable photodetection. The resonant wavelength and the polarization response of the device can be engineered by manipulating the widths of the fins and the metallic slits.

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5. References:

[1] D .A. B. Miller, "Device requirements for optical interconnects to Silicon chips", Proceedings of the IEEE **97,** 1166-1185 (2009).
[2] D. K. Gramotnev and S. Bozhevolnyi, "Plasmonics beyond the diffraction limit", Nature Photonics, **4**, 83-91 (2010).
[3] J. S. White et. al, "Extraordinary optical absorption through subwavelength slits", Optics Letters, **34**, 686-688 (2009)
[4] S. M. Sze, *Physics of semiconductor devices* (John Wiley & Sons, 1981), 245-311.
[5] P. Neutens et. al, "Electrical detection of confined gap plasmons in metal-insulator-metal waveguides", Nature Photonics, **3**, 283-286 (2009)