Highly sensitive wavelength-scale amorphous hybrid plasmonic detectors: supplementary material

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1. ANALYSIS OF THE HYBRID-SPP WAVEGUIDE

Compared to conventional TIR structures, SPP modes are capable of confining light on subwavelength scales, thus enabling photonic devices with very compact footprint and much higher density. The complex permittivity of metals at optical frequencies lead to significant losses, limiting propagation lengths to a few microns before power is attenuated below detectable levels. Due to these losses, it seems that plasmonic modes may never outperform their all-dielectric counterparts to transport light between different points. However, if these losses are reduced beyond a certain level, plasmonic structures may provide the optimum medium to accommodate truly nano-scale devices in all three dimensions, thereby empowering a contender to the all-dielectric Si platform used at present.

The hybrid-SPP waveguide shown in Fig. S1 is formed by a superposition of single-sided HPW with SPP mode coupled through a thin metal film. The asymmetry does not only come from permittivity differences, but the original modes are also fundamentally different. When decoupled, both HPW and SPP modes have drastically different propagation constants and evolve differently when the dimensions are varied. Yet, coupled supermodes can still be excited when the metal film is sufficiently thin. As Fig. S1 shows, the hybrid-SPP waveguide can be treated as two individual decoupled HPW and SPP waveguides when the metal film is thicker than its skin depth. As the thickness is reduced below skin depth, coupled supermodes between HPW and SPP arise as the evanescent fields extend to the opposite side and perturb each other, as long as the effective index difference is small. The combination of HPW and SPP into one structure also suggests light-matter interaction on two types of plasmonic interfaces, metal with high-index and metal with low-index, allowing one waveguide to support multiple applications.

In Fig. S2, the dispersion properties of the various supermodes are plotted. To illustrate the effects of field matching,

Fig. S1. Hybrid-SPP waveguide can be treated as superposition of two individual decoupled HPW and SPP modes when the metal film is thicker than its skin depth.

HPW side is kept constant as thickness of the SPP-side high-index Si layer (t_A) is varied from 100 nm to 300 nm. Coupling of the HPW and SPP forms a fundamental antisymmetric and a higher-order symmetric supermodes similar to a thin metal film embedded in a homogeneous dielectric bulk.

Fig. S2. Propagation constant and extinction coefficient of the decoupled HPW and SPP modes, and supermodes in the coupled hybrid-SPP in 1D.

From coupled mode analysis, antisymmetric corre-
sponds to in-phase coupling of the HPW and SPP modes, resulting in overlap with the metal leading to significant absorption losses. On the opposite, the out-of-phase coupling of the symmetric mode minimizes overlap as a result of destructive interference, lending support for long-range propagation with losses much lower than either SPP and HPW. In this 1D analysis, the optimal $t_{\text{eff}}$ thickness is 148 nm for a slab mode extending to infinity in the horizontal direction.

The hybrid-SPP waveguide displays interesting effects as we move to 2D confinement. The mode effective index and propagation loss of the symmetric supermode are plotted in Fig. S3 as function of width and wavelength for a hybrid-SPP structure with $t_{\text{eff}}$ of 185 nm. This thickness is based on loss optimization analysis for a minimum realizable width of 200 nm due to limitations in our fabrication processes. From the dispersion plot, it is observed that the symmetric supermode of a 200 nm-wide waveguide can operate up to a wavelength of 1.8 μm, after which the optical mode becomes leaky as the mode index drops below the substrate index.

In Fig. S3, it is observed that the absorption losses of the symmetric mode increases dramatically as width approaches 620 nm due to the combined effects of field symmetry breaking and modal evolution asymmetry. This behavior enables the design of devices that benefit from both low and high absorption for the same mode under the same fabrication steps. The field profiles for $E_x$, $D_y$ and $E_z$ are shown in Fig. S4 as the mode changes from a width of 200 nm to 620 nm. For $E_x$ and $E_z$, only fields inside the metal are shown in order to highlight field symmetry and overlap. The loss contribution from the x and z components is dependent on the location of zero-crossing and indicates the amount of overlap with the metal. At wider widths, $E_z$ overlap with the metal is stronger as the position for zero-crossing does not extend to the edges as in the narrow case. For $E_x$ at 200 nm, a deformed quadrupole field distribution is formed from fields extending inwards from the metal corners, thus expanding the zero-crossing and reducing field overlap in two axes. As width increases, $E_z$ becomes a dipole instead and the horizontal zero-crossing is entirely shifted out of the metal, thus maximizing $E_x$ overlap. The modal evolution asymmetry in the hybrid-SPP waveguide is also evidenced in the $D_y$ profile. The higher effective index of the SPP side allows it to start supporting higher order modes at much reduced widths than the HPW side. As a result of the evolution asymmetry, the HPW can couple to higher order SPP modes to form hybridized supermodes, which further enhances the field symmetry breaking in order to increase field overlap with the metal. In the 620 nm case, TM$_{02}$ hybridizes with TM$_{04}$ as their effective indices cross, but absorption drops again at wider dimensions as the contrast becomes larger until the next hybridization point is reached.

![Image](Fig. S4. (a) $D_y$, (b) $E_y$, and (c) $E_z$ profiles for the TM$_{00}$ mode at 200 nm and 620 nm. For $E_x$ and $E_z$, only fields within the metal layer are shown to highlight the evolution of mode asymmetry. Dashed black line indicates where $E_x$ and $E_z$ cross zero.)

### 2. PHOTODETECTOR MODELING

Modeling of the hybrid-SPP photodetector consists of two parts, optically-induced internal photodetection and dark current generation. Internal photoemission is the optical excitation of photocarriers in a metallic emitter and subsequent generation of photocurrent as these excited carriers have enough energy to cross a Schottky barrier.

The total optical absorbance of the hybrid-SPP waveguide is given by the mode attenuation $\alpha$ multiplied by the detector length $L_d$. As the mode loss $\gamma_{\text{dB}}$ is expressed in units of $\text{dB/μm}$, the attenuation coefficient $\alpha$ and absorbance $A$ are given by:

$$A = 1 - e^{-\alpha L_d} \quad \text{(S1a)}$$

$$\alpha = \frac{\gamma_{\text{dB}}}{10 \log(e)} \quad \text{(S1b)}$$

The internal quantum efficiency $\eta_i$ or internal photoyield is the amount of absorbed photons per second that can be efficiently converted to carriers that contribute to photocurrent. This metric determines how many of the hot carriers generated by absorption have enough energy to cross $\Phi_B$ when they arrive at the Schottky interface. Scattering events due to collisions with phonons, imperfections, and cold electrons can contribute carrier energy loss within the metal, and modeled via the Schottky carrier attenuation length $L_\phi$ defined as the distance travelled before energy decays by a factor of $e^{-1}$. From the models proposed by Berini [1, 2], the internal quantum efficiency of a thin-film single-barrier Schottky detector is given by:

$$\eta_i = \frac{1}{h\nu} \int_{\Phi_B}^{E_0} P^i(E_0) \, dE_0 \quad \text{(S2)}$$

where $P^i(E_0)$ is the sum of carrier emission probability with energy level $E_0 > \Phi_B$, given as:

$$P^i(E_0) = P_0 + (1 - P_0)P_1 + (1 - P_0)(1 - P_1)P_2 + \ldots + P_0 \prod_{k=0}^{n-1} (1 - P_k) \quad \text{(S3)}$$
The probability $P_k$ for energy level $E_k$ after $k$ round trips between the two interfaces of the metal is:

$$
P_k = \frac{1}{2}
\left(1 - \sqrt{\frac{\Phi_B}{E_k}}\right)
$$

(S4a)

$$
E_k = E_0 e^{-2k}\rho
$$

(S4b)

where $t$ is the metal thickness and total number of round trips between the interfaces before $E_k$ falls below $\Phi_B$ is given by:

$$
n = \left[\frac{L}{2\rho} \ln\left(\frac{E_0}{\Phi_B}\right)\right]
$$

(S5)

In Eq. S4, the emission probability of a photogenerated carrier is determined by whether it has enough escape momentum component normal to the interface to overcome $\Phi_B$. Eq. S5 suggests an increase of emission probability for hot carriers in metal films with a thickness much lower than its attenuation length and describes the probability of a carrier to be emitted over the barrier even after multiple reflections within the metal interfaces.

The external quantum efficiency is the internal quantum efficiency multiplied by the optical absorbtion ($\eta_e = A\eta_i$). Herein exists a trade-off between $\eta_i$ and $A$, as the former benefits from a thin metal layer in order to increase carrier escape probability through multiple interface reflections, but optical absorption is reduced due to the decreased overlap, which increases the detector footprint in typical cases. However, it was shown earlier that the hybrid-SPP waveguide can alleviate this trade-off and achieve high absorption for a 10nm-thin metal layer by breaking field symmetry and maximizing metal overlap instead.

The responsivity of a photodetector is the photoresponse or amount of photocurrent generated from incident optical power in units of $A/W$, given by:

$$
R = \frac{\eta_e}{h\nu}
$$

(S6)

Therefore, in order to obtain a large photoresponse, both a low Schottky barrier height and high absorptance are essential. However, a lower barrier height also leads to increased dark currents and idle power consumption. The dark current density of a reverse biased Schottky junction is given by thermionic emission theory [3]:

$$
I_d = A^{**} T^2 e^{-\frac{\Phi_B}{kT}}
$$

(S7)

where $A^{**}$ is the carrier effective Richardson constant in the semiconductor, $T$ is the operation temperature and $V_T$ is the thermal voltage $kT$. The dark current is then $I_d = A_c I_d$, where $A_c$ is the active contact junction area. The sensitivity or minimum detectable power under CW illumination is defined in the model proposed by Berini as 1dB above the incident power required to generate a photocurrent equal to the dark current, in units of $dBm$:

$$
S_{min} = 10 \log \left(\frac{I_d}{R}\right) + 1
$$

(S8)

The dark current of a photodetector is an important metric as it not only leads to increased power consumption, but also in operation temperature as the additional power dissipates through the sample and feedbacks positively into the device. Design of the electrical contacts is based on the MSM configuration, which consists of two back-to-back reverse biased Schottky junctions separated by a semiconductor of thickness $L_s$. While MSM structures typically exhibit large dark currents due to thermionic emission over two junctions, suppression of dark currents can be achieved by designing small contact areas.

For a lightly doped semiconductor, under increasing reverse voltage, there exists a flat-band condition for which free carriers are fully depleted, allowing for photogenerated carriers to be quickly swept from emitter to collector. The corresponding flat-band voltage is given by:

$$
V_{FB} = \frac{q N L_s^2}{2\epsilon_B}
$$

(S9)

where $N$ is the semiconductor doping, $\epsilon_s$ is the material permittivity of Si, and $L_s$ is the top-side Si thickness. Under the flat-band condition, dark current density is given by the summation of electron injection at the cathode and hole injection at the anode:

$$
I_d = I_{dn} + I_{dp} = A_{n}^{**} T^2 e^{-\frac{\Phi_{Bn}}{kT}} + A_{p}^{**} T^2 e^{-\frac{\Phi_{Bp}}{kT}}
$$

(S10)

The total dark current is then given by $I_d = I_{cn} I_{dn} + A_{cp} I_{dp}$, in which $A_{cn}$ and $A_{cp}$ are the contact junction areas of the cathode and anode respectively. It should also be noted that at applied voltages greater than flat-band, the effective Schottky barrier height decreases due to image force lowering effects, given by:

$$
\Phi_{Bn} = \Phi_{Bn0} - \Delta \Phi_{Bn}
$$

(S11a)

$$
\Phi_{Bp} = \Phi_{Bp0} - \Delta \Phi_{Bp}
$$

(S11b)

where $\Delta \Phi_B$ is the potential barrier lowering due to applied voltage:

$$
\Delta \Phi_B = \sqrt{\frac{V - V_{FB}}{4\pi e L_s/2}}
$$

(S12)

observing that by applying the image force lowering effect, higher $\eta_i$ can be achieved but at the same time, $I_d$ also increases.

For computational modeling of a 10pm-long hybrid-SPP photodetector, the carrier attenuation length $L$ of Al is assumed to be 100nm and Schottky barrier heights for Al/p-Si junctions are taken as $\Phi_{Bn0} = 0.54eV$ and $\Phi_{Bp0} = 0.58eV$ [3]. In order to utilize the lower n-barrier for carrier emission, the 10nm-thick Al emitter is biased at a negative potential with respect to the collector on top. To suppress dark currents from the collector, contact junction area is reduced to $1 \times 1\mu m^2$. Given an absorption of 1.0dB/\mu m for the symmetric supermode, the internal responsivity, dark currents and minimum sensitivity are plotted in Fig. S5. With this design, a responsivity of 30mA/W can be achieved under 2V. The dark current density is on the order of $1nA/\mu m^2$ and under the proposed contact junction designs, total dark currents can be reduced to $nA$ range or lower, enabling a sensitive detector at $-50dBm$ at low bias.

3. SUPPLEMENTARY EXPERIMENTAL RESULTS

A. Series Resistance

The model provided in Section 2 modeled the voltage drop to be across the reversed bias junction with negligible series resistance in the silicon film and forward junction contact. However, in our experimental devices the series resistance acted as a voltage divider and caused the effective bias at the reverse junction
to be much lower. This can be attributed to the poor conductivity in the film quality and insufficient doping of the amorphous silicon sputtering target used.

The series resistance of two back-to-back Schottky junctions can be approximated via $R_s = dV/dI$ at the linear high voltage bias regime of the I-V curves. Using this approximation, the static series resistance for the devices of various lengths are plotted in Fig. S6. The large series resistance is the primary factor for the increase in bias required to observe photocurrents as well as the low responsivity in the experimental devices compared to theory. The performance of our photodetectors can improve by applying controlled doping concentrations on the aSi film.

**C. Sample Variations**

The variations in currents measured can be attributed to factors such as non-uniform formation of Schottky junctions which are known to be difficult to control and contact pad resistance due to damage from device probing. The dark currents of the devices are plotted in Fig. S8 with the standard deviation across multiple devices.

**D. Frequency Response**

Measurement of the experimental frequency response was limited within a range of 100MHz to 2.5GHz due to the bandwidth of the optical modulator, amplifiers and signal source. To estimate the RC-limited bandwidth, the parasitic capacitances were measured for devices of various lengths using a HP4280 1MHz C Meter, shown in Fig. S9.

**4. COMPARISON OF EXPERIMENTAL IPE PHOTODETECTORS**

In Table S1, the hybrid-SPP photodetector is placed in comparison with previous experimental works reported in literature. These devices are traveling-wave detectors based on the internal photoemission process and do not include surface-illuminated photodetection. The following metrics are compared: materials used to form the active junction, device length, optical power coupling efficiency, responsivity, dark currents, minimum sensitivity, operating wavelength range and tested temperature range.

Our device is the first report of a hybrid plasmonic waveguide used for photodetection based on amorphous materials.
and still be able to achieve better performance in various metrics compared to crystalline counterparts, most notably the lowest minimum sensitivity reported experimentally due to low dark currents. The use of aluminum as a metal layer compatible with CMOS processes and deposited amorphous silicon allow non-intrusive back-end integration of on-chip optoelectronics.

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|                 | Materials (Active junction) | Length (µm) | Coupling Efficiency | Responsivity (mA/W) | Dark Current (dBm) | $S_{min}$ (µm) | $\lambda$ (µm) | Temperature (°C) |
|----------------|-----------------------------|-------------|---------------------|---------------------|-------------------|---------------|----------------|-----------------|
| Strip waveguide [5] | Al-cSi                      | 35          | 2%*                | 1 (λ = 1.28µm)      | 6µA              | 8§            | 1.28 – 1.62  | RT              |
| Strip waveguide [5] | Au-cSi                      | 80          | 4%*                | 0.38 (λ = 1.28µm)   | 10nA             | −14§          | 1.28 – 1.62 | RT              |
| Strip waveguide [6] | Au-cSi                      | 40 – 60     | 16%*               | 1 (λ = 1.55µm)      | —                | —             | —             | 1.31, 1.55      | RT              |
| Silicide on SOI [7] | NiSi$_2$-cSi                | 23.4        | —†                 | 4.6 (λ = 1.55µm)    | 3nA              | −30§          | 1.52 – 1.62  | 20 – 120         |                 |
| MSM [8]          | Cu-cSi                      | —†          | 9%†                | 1.5 – 4.5 (λ = 1.55µm) | 1.8 – 2.2nA      | −29§          | 1.55         | RT              |
| Slot waveguide [9] | Au-cSi-Ti                   | 4 – 20      | 50%†               | 14 – 126 (λ = 1.55µm) | 0.3 – 10µA       | −16§          | 1.55         | RT              |
| This work        | Al-αSi                      | 5 – 20      | 70%†               | 0.2 – 5 (λ = 1.55µm) | 0.2 – 20nA       | −35           | 1.2 – 1.575  | 15 – 100         |                 |

* End-facet coupling from a single-mode fiber
† On-chip coupling from an integrated silicon nanowire
‡ Metric not reported
§ Minimum sensitivity calculated from the reported responsivity and dark currents via Equation S8

Table S1. Comparison of experimentally demonstrated IPE photodetectors reported in literature with the hybrid-SPP photodetector.