Supplemental Document

Optics EXPRESS

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Supplement DOI: https://doi.org/10.6084/m9.figshare.21153904

Parent Article DOI: https://doi.org/10.1364/OE.468917

Plasmonic *hot-electron* reconfigurable photodetector based on phase-change material Sb_2S_3

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1. Quantum efficiency

In general, hot-electron based photodetectors present low quantum efficiencies. Nevertheless, this is a compromised condition in exchange for absorption at energies below the band gap. The quantum efficiency depends on the operational spectral range of the photodetector. As the wavelength is increased, the quantum efficiency decreases. This is why, as the proposed photodetector works in the telecom wavelengths, the quantum efficiency is low. In Fig. S1, we represent the quantum efficiency for both phases. For comparison, another hot electron photodetector (with no reconfigurability) working at the C band has been reported in literature with quantum efficiency of 0.2%. [1].

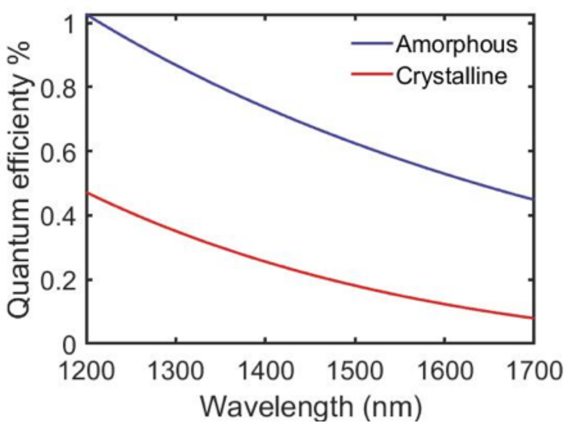

Fig. S1. Quantum efficiency of the proposed photodetector as a function of the wavelength for both phases of Sb_2S_3 (crystalline in blue and amorphous in red) . .

2. Thickness dependence and substrate effect.

In the manuscript, Sb_2S_3 has been considered as substrate (i.e., Sb_2S_3 of infinite thickness). Nevertheless, the experimentally switch of Sb_2S_3 between its both phases has only been demonstrated for thicknesses in the range of tens of nanometers. Therefore, for a more realistic consideration of the studied system, the first step is to calculate the plasmon depth in the Sb_2S_3 as function of the PCM layer. This penetration depth d can be calculated from equation 1.

$$d = \frac{\lambda}{2\pi} \cdot \sqrt{\frac{|\epsilon_g| + \epsilon_{PCM}}{\epsilon_{PCM}^2}} \tag{1}$$

where λ is the wavelength, and ϵ_{PCM} and ϵ_g are the real part of the dielectric function of the PCM and gold respectively.

As shown in Figure S2, the plasmon depth is around 253 nm for both resonant wavelengths and both phases (1310 – amorphous and 1550 nm- crystalline).

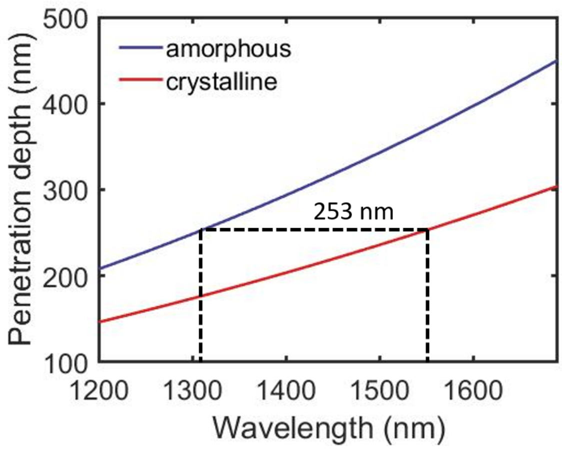

Fig. S2. Plasmon penetration depth in Sb_2S_3 for both phases (amorphous in blue and crystalline in red). The plasmon depth for both resonant wavelengths: 1310 nm - amorphous and 1550 nm - crystalline is around 253 nm.

The second step is to calculate the absorbance of the proposed design for different thicknesses of the PCM in order to make a more realistic stimation of the photoresponsivity of the device. The PCM is on top on a silicon substrate. In Figure S3, the second plasmon order has been simulated for different thicknesses of antimony sulphide. For thicknesses higher than 300 nm (near plasmon depth) plasmon peaks can be generated. However, the amplitude of these peaks is not as high as for the infinite thickness reported in the paper. Thickness should be increased for this purpose. From a thickness of 800 nm the absorbance is exactly as if the PCM is treated as a substrate. So, this should be the thickness of the PCM to achieve the results obtained in the manuscript.

The same simulations have been performed setting different materials as substrate as shown Figure S4. For a thickness of 800 nm the proposed design for the second plasmon order is simulated over a glass (SiO_2) and a sapphire (α-Al_2O_3) substrate. In this case, as the refractive index of the PCM is higher than the one of the substrate materials (SiO_2 and α-Al_2O_3), interference fringes are produced leading to the appearance of extra peaks in the absorbance spectra. To avoid this, only a Si, or other materials with a higher refractive index than the PCM, have to be used as substrate.

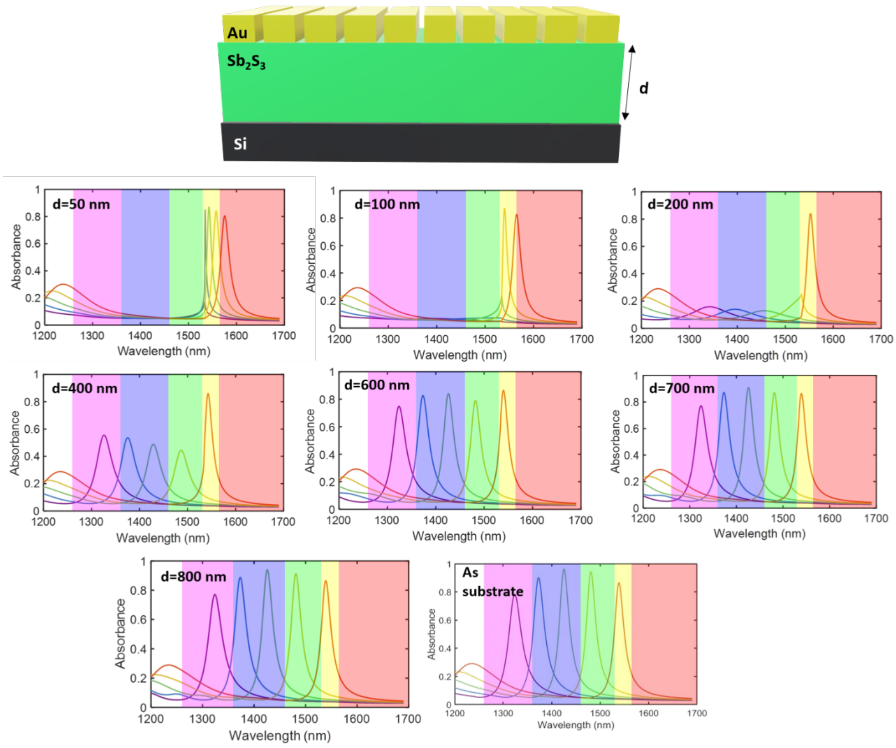

Fig. S3. Absorption spectra of the proposed photodetector for the second plasmon order and for amorphous, crystalline and the intermediate states by changing the thickness d of Sb_2S_3 over a silicon substrate. The thicknesses have been varied from d=50 nm to d=800 nm and finally, considered as a substrate.

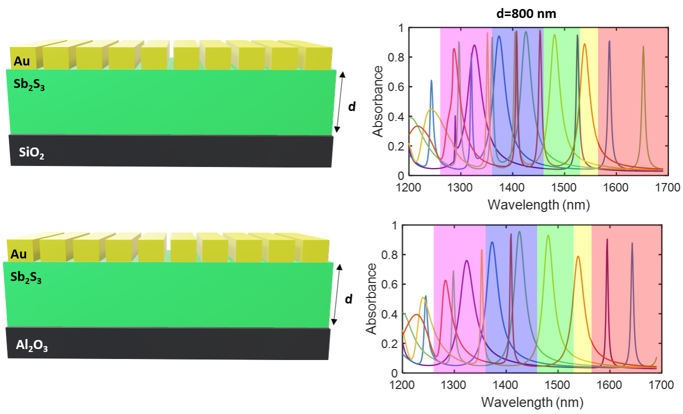

Fig. S4. Absorption spectra of the proposed photodetector for the second plasmon order and for amorphous, crystalline and the intermediate states for a thickness d = 800 nm of Sb_2S_3 over a glass and a sapphire substrate.

3. The use of a capping layer

A capping layer has been modelled in order to avoid the oxidation of the PCM and to prevent the reshaping of the grating at high temperatures required for amorphization.

The capping layer can be located between the gold ribs and the PCM. 3 different capping layers have been simulated. The materials considered for the capping layer are the most common ones used in experiments: SiO_2, Si_3N_4 and ZnS. The plasmonic response is analysed for the three materials and for thickness ranging from 0 to 5 nm. This study has been performed for the second plasmon order as it is the one producing higher absorbance. The introduction of the capping layer does not alter the values of the absorbance, and therefore, of the photoresponsivity. Nevertheless, the plasmon resonances are blueshifted as we are introducing another medium with lower refractive index than the PCM. As shown in Figure S5, the higher refractive index of the capping layer, the lower the blueshift of the resonance. This shift due to the introduction of the capping layer can be considered to recalculate the periods.

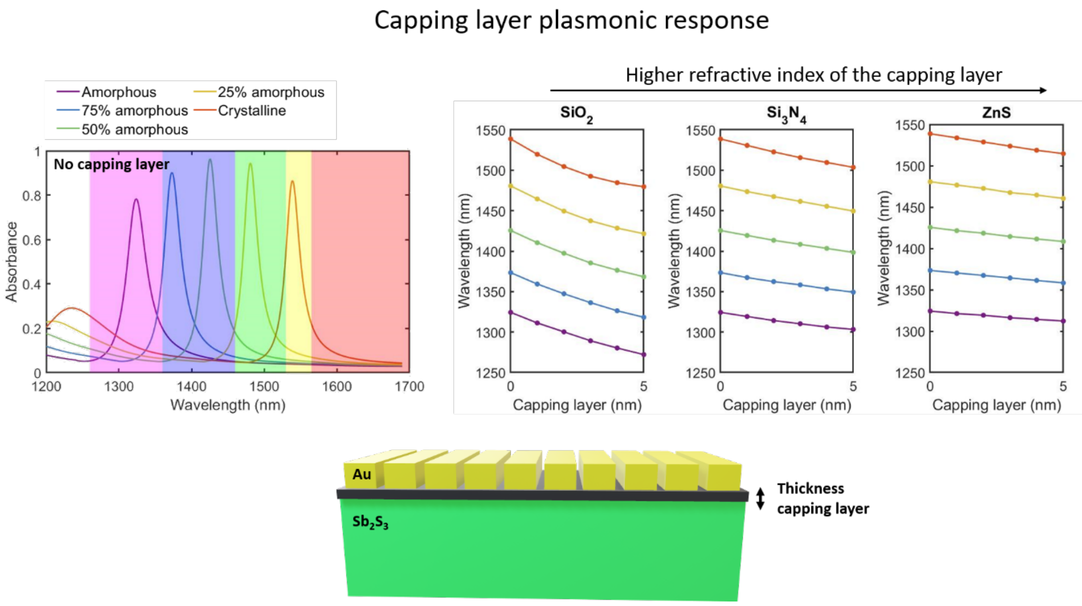

Fig. S5. Absorption spectra of the proposed photodetector for the second plasmon order and for amorphous, crystalline and the intermediate states considering Sb_2S_3 as a substrate. The wavelength of the resonant peaks are studied as a function of the thickness of the capping layer. The different materials for the capping layer are: SiO_2, Si_3N_4 and ZnS and its thickness have been varied from 0 to 5 nm. This capping layer is located between the gold ribs and the PCM.

It should be noted that the introduction of a capping layer between the metal and the PCM may affect the Schottky barrier. As the energy band gaps of the capping layers (SiO_2 - (7.5 -9.2 eV) [2], Si_3N_4 - (4.5-5.33 eV) [3] and ZnS - (3.6 eV) [4]) are higher than the ones of the Sb_2S_3, the value of the Schottky barrier its expected to increase. Moreover, as the Schottky barrier increases, the photoresponsivity is expected to decrease. To the best of our knowledge, no theoretical or experimental data is available in literature to predict the alteration in the value of the Schottky battier by introducing any of the previous layers between Au and Sb_2S_3. From this arguments, what can be expected is that ZnS is the best candidate as: (i) the blueshift in the plasmonic resonance is lower, and (ii) the Schottky barrier will experience the slightest modification as ZnS presents the lower bandgap.

References

1. A. Sobhani, M. W. Knight, Y. Wang, B. Zheng, N. S. King, L. V. Brown, Z. Fang, P. Nordlander, and N. J. Halas, "Narrowband photodetection in the near-infrared with a plasmon-induced hot electron device," Nat. communications **4**, 1–6 (2013).
2. E. Güler, G. Uğur, Ş. Uğur, and M. Güler, "A theoretical study for the band gap energies of the most common silica polymorphs," Chin. J. Phys. **65**, 472–480 (2020).
3. J. Bauer, "Optical properties, band gap, and surface roughness of si3n4," physica status solidi (a) **39**, 411–418 (1977).
4. P. D'Amico, A. Calzolari, A. Ruini, and A. Catellani, "New energy with zns: novel applications for a standard transparent compound," Sci. reports **7**, 1–9 (2017).