UV &Visible Plasmonic Metamaterials Made of Topological Insulator

Jun-Yu Ou[1], Jin-Kyu So[1*], Giorgio Adamo[2], Azat Sulaev[3], Lan Wang[3], and Nikolay I. Zheludev[1,2]
[1] *Optoelectronics Research Centre & Centre for Photonic Metamaterials, University of Southampton, SO17 1BJ, UK*
[2] *Centre for Disruptive Photonic Technologies, Nanyanag Technological University, Singapore*
[3] *School of Physical and Mathematical Sciences, Nanyang Technological University, 637371, Singapore*
**js1m10@orc.soton.ac.uk*

Abstract: Plasmonic resonances are observed in metamaterials made of a topological insulator, $Bi_{1.5}Sb_{0.5}Te_{1.8}Se_{1.2}$, at the UV and visible frequencies due to the material's interband transition and nontrivial surface conducting state.
OCIS codes: (240.6680) Surface plasmons; (160.3918) Metamaterials; (160.4670) Optical materials

We provide the first demonstration of plasmonic metamaterials made of a topological insulator, $Bi_{1.5}Sb_{0.5}Te_{1.8}Se_{1.2}$ (BSTS), working at the UV and visible frequencies where finding a good plasmonic material is extremely challenging. Metamaterials fabricated from the BSTS crystal show plasmonic resonances from 350 nm to 550 nm while surface gratings exhibit cathodoluminescence peaks from 230 nm to 1050 nm. The negative permittivity underpinning plasmonic response is attributed to the combination of bulk interband transitions and surface contribution of the topologically protected states. This finding of new class of materials with high-frequency plasmonic response could advance plasmonics in view of merging plasmonic functionality with electronics thanks to the nature of the material.

Gold and silver are the two best known materials supporting collective oscillations of charge carriers associated with light, so-called plasmons. Their superb performance at optical frequencies has led to a plethora of application enabled by the huge field enhancement and confinement. However, materials with a good plasmonic behavior in other frequency regimes are scarce in nature and the need for plasmonic materials with compatibility to silicon photonics and additional functionalities thrusted the search for alternative plasmonic materials. Such attempts harvested several alternatives mostly in the infrared, where it is mainly done by diluting metals or increasing the density of charge carriers in semiconductors [1]. Two-dimensional plasmonic materials such as graphene are another option in the infrared and topological insulators recently joined in this category [2]. Nevertheless, the UV-visible part of the spectrum remains an extremely challenging domain for plasmonics as gold and silver have losses there, while the above mentioned approaches with artificially doped semiconductors and graphene don't work in this regime. The search for plasmonic metals in this spectral range is still ongoing, where aluminum surfaces as the most appealing one among them given that a controlled preparation and material analysis are accompanied to regulate the unavoidable oxidation.

Here, we show that a pristine semiconducting material, $Bi_{1.5}Sb_{0.5}Te_{1.8}Se_{1.2}$ (BSTS), which is also known as a topological insulator, could be an alternative plasmonic material to gold and silver at this challenging UV-visible part of the spectrum. Our BSTS single crystals were synthesized by melting high-purity (99.9999%) Bi, Sb, Te and Se with molar ratio 1.5:0.5:1.8:1.2 at 950℃ in an evacuated quartz tube. The temperature was then gradually decreased to room temperature over a span of three weeks [3]. The BSTS single crystal was then cleaved along the (100) family of planes to a thickness of ~0.5 mm. The optical properties of the unstructured surface were first revealed by multiple-angle spectroscopic ellipsometry. The measured dielectric function in Fig. 1(a) clearly shows negative permittivity in wavelengths, 200 – 670 nm, which is rarely seen at the first absorption edge of semiconductors in nature. The measured dielectric function was fitted with a two-layer material system consisting of a bulk semiconductor with a thin metal film on top [3], where each layer was modeled by the Tauc-Lorentz and Drude dispersions, respectively. The best-fit parameters (solid lines) [4] conform to the previously reported values found for this material from the independent DC conductivity measurements [3] and corroborate very well with the results of ab initio calculations of dielectric functions of similar alloys [5], which validates the proposed two-layer material system.

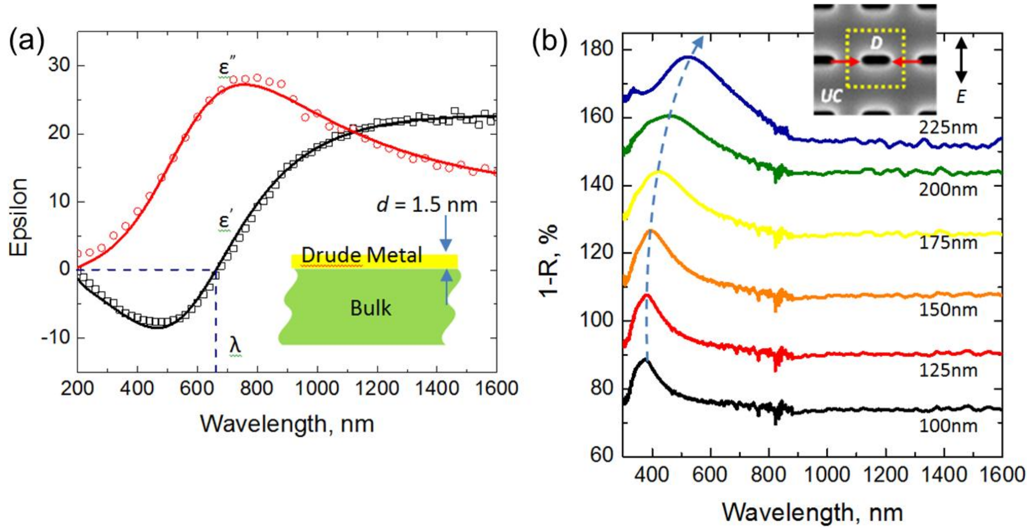

Fig. 1: (a) Dielectric function of the crystal retrieved from spectroscopic ellipsometry. The inset shows a sketch of the layer-on-bulk model of the crystal. Experimental points are presented together with the modeling data (solid lines). (b) Absorption spectra, 1-*R*, of various nano-slit arrays with lengths *D* = 100-225 nm for light polarized perpendicular to the slits. The inset shows the SEM image of a nano-slit array with *D* = 150 nm.

To verify the plasmonic behavior of the BSTS crystal in nanostructures, we manufactured a series of nano-slit antenna arrays with linear grooves cut into the surface of the single crystal using focused-ion-beam milling. In the nano-slit antenna array the slit length *D* was varied from 100 nm to 275 nm and the period of the slit (unit cell size, *UC*) was kept at 300 nm. The plasmonic response of the fabricated nano-slit metamaterials were studied by measuring their reflection spectra $R(\lambda)$ and their corresponding absorption spectra $A(\lambda) = 1 - R(\lambda)$ for two incident polarizations perpendicular and parallel to the nano-slits. A profound resonance in plasmonic absorption can be seen for the perpendicular polarization (Fig. 1(b)), where slits in the conductive surface, the “anti-dipole”, will be resonant for perpendicular polarization. Hence, the resonant wavelength increases monotonously with the length of the groove as can be seen in Fig. 1(b). As expected, no plasmonic resonance can be found in the parallel polarization. Full 3D Maxwell calculations of the reflectivity spectra obtained on the basis of ellipsometry data strongly corroborate experimental results [4]. Surprisingly, the plasmonic response was also found for wavelengths longer than 670 nm [4] which is beyond the negative permittivity regime of the bulk semiconductor. Here, we argue that the observation of the CL peaks for wavelengths beyond 670 nm is a clear evidence of plasmonic contribution of the surface conducting state.

In summary, we have demonstrated the plasmonic behavior of a topological insulator, $Bi_{1.5}Sb_{0.5}Te_{1.8}Se_{1.2}$, at optical frequencies. It resulted from a combination of contributions from the topologically protected surface conducting state and a strong dispersion due to the interband transition. The optical and electron beam excitation of the material demonstrated the existence of the plasmonic response with quality factor of about four that is sufficient for many sensors, light localization and metamaterials applications and that outperforms the noble metals in the UV-blue-green parts of the spectrum.

[1] G. V. Naik, V. M. Shalaev and A. Boltasseva, “Alternative Plasmonic Materials: Beyond Gold and Silver”, Adv. Mater. **25**, 3264 (2013).

[2] P. Di Pietro, M. Ortolani, O. Limaj, A. Di Gaspare, V. Giliberti, F. Giorgianni, M. Brahlek, N. Bansal, N. Koirala and S. Oh, “Observation of Dirac plasmons in a topological insulator”, Nat. Nanotechnol. **8**, 556 (2013).

[3] B. Xia, P. Ren, A. Sulaev, P. Liu, S.-Q. Shen and L. Wang, Indications of surface-dominated transport in single crystalline nanoflake devices of topological insulator $Bi_{1.5}Sb_{0.5}Te_{1.8}Se_{1.2}$, Phys. Rev. B **87**, 085442 (2013).

[4] J. Y. Ou, J. K. So, G. Adamo, A. Sulaev, L. Wang, and N. I. Zheludev, “Ultraviolet and visible range plasmonics of a topological insulator”, arXiv.org 1401.1415 (2014).

[5] Y. Sharma and P. Srivastava, “First-principles Study of Electronic and Optical Properties of BiSe in its Trigonal and Orthorhombic Phases”, AIP Conference Proceedings **1249**, 183 (2010).