Plasmonics of topological insulators at UV-visible frequencies

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Abstract

We report the first observation of the plasmonic behavior of a semiconducting material, $Bi_{1.5}Sb_{0.5}Te_{1.8}Se_{1.2}$, at the UV and visible frequencies, which was revealed by spectroscopic ellipsometry, reflection and cathodoluminescence measurements. Its plasmonic response originates from the negative dielectric permittivity at the material's first absorption edge, which is rarely seen in nature, together with the contribution of the nontrivial surface conducting states 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 [2] and topological insulators recently joined in this category [3]. 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 [4].

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°C in an evacuated quartz tube. The temperature was then gradually decreased to room temperature over a span of three weeks [5]. 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 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 [5], where each layer was modeled by the Tauc-Lorentz and Drude dispersions, respectively. The best-fit parameters (solid lines) [6] conform to the previously reported values found for this material from the independent DC conductivity measurements [5] and corroborate very well with the results of *ab initio* calculations of dielectric functions of similar alloys [7], which validates the proposed two-layer material system.

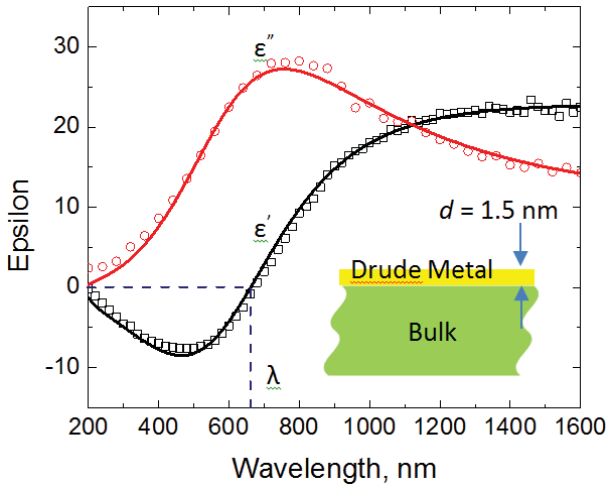

Figure 1: Dielectric function of the crystal retrieved from spectroscopic ellipsometry. The inset shows a sketch of the layer-on-bulk model of the crystal. Experimental points are presented together with the modeling data (solid lines).

To verify the plasmonic behavior of $Bi_{1.5}Sb_{0.5}Te_{1.8}Se_{1.2}$ in nanostructures, we manufactured a series of metamaterials, nano-slit antenna arrays with linear grooves cut into the surface of the crystal and gratings on the crystal surface 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(λ)* and their corresponding absorption spectra *A(λ)*= 1 - *R(λ)* 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. 2), 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. 2. 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 [6].

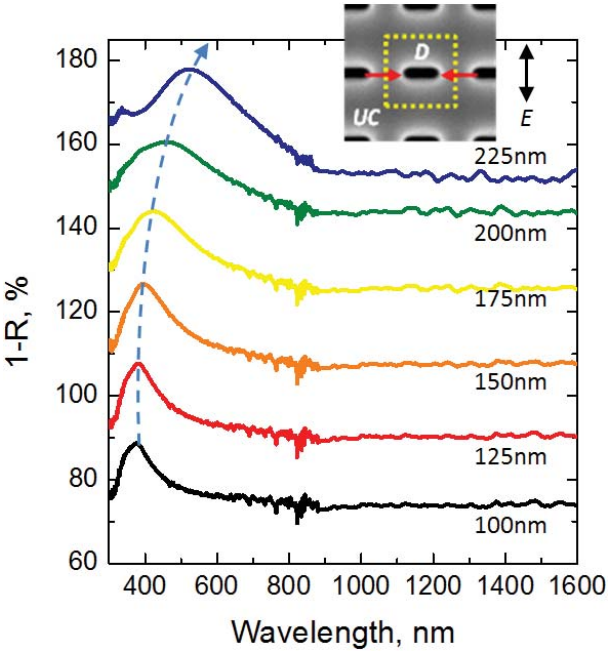

Figure 2: Absorption spectra, 1-*R*, of various nano-slit arrays with lengths *D* = 100-225 nm for light polarized perpendicular to the slits. The inset shows the SEM image of a nano-slit array with *D* = 150 nm.

In another series of experiments, we investigated the optical response and cathodoluminescence (CL) spectra of gratings fabricated on the surface of topological insulator. 70 nm deep gratings with the periods *P* = 200-1500 nm were fabricated on the surface of a bulk BSTS crystal. The plasmonic response was found when the gratings were illuminated with the polarization perpendicular to the grating rulings, while featureless absorption spectra were observed for the parallel polarization. Moreover, plasmonic peaks were also visible for wavelengths longer than 670 nm [6] which is beyond the negative permittivity regime of the bulk semiconductor. This finding was corroborated by cathodoluminescent measurements on the same gratings, which showed plasmonic peaks matching the absorption peaks in the range from 230 nm to 1050 nm. 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 topological conductivity 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. We believe that the importance of our results is in the identification of new class of materials with high-frequency plasmonic response where plasmonic functionality can be directly integrated with electronics thanks to the semiconductor nature of the material.

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