Terahertz and Infrared study of topological insulators

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1 Introduction

Topological Insulators (TIs) are a new exotic class of materials, which is one of the most studied and intriguing issue at the focus in condensed matter physics today. TIs exhibit a small bulk band gap like ordinary semiconductors, but have exotic protected 2D conducting states on their edge or surface. This means that the topology, associated with the electronic wavefunctions of the system, discontinuously changes when passing from the bulk to the surface [1]. These edge states arise from a strong spin-orbit coupling in those materials, and they are backscattering protected, i.e. not sensitive to disorder (except that coming from magnetic impurities). Moreover these states are spin-locked. This means that although the carrier motion is allowed in any direction of the 2D surfaces, the direction uniquely determines the electron spin polarization and viceversa.

TIs surface charge transport is carried out by Dirac fermions (like in graphene), with a very high surface carrier density \( n \geq 10^{13}\text{cm}^{-2} \) and mobility, compared to the typical values for other 2-Dimensional electron gases present in conventional semiconductors [2].

The physical properties cited before render TIs deeply suitable for novel applications. In particular: 1) the use of collective charge excitations at the TI surface for signal propagation [3]; 2) the modulation of the charge degree of freedom through a magnetic field; 3) the modulation of the spin degree of freedom through an electric field.

This PhD thesis project concerns with the investigation of the terahertz (THz) and infrared (IR) properties of TI thin films and single crystals and with the design, fabrication and characterization of TI-based plasmonic devices, by means of Electron Beam Lithography (EBL) patterning.
2 Steady-state study of topological insulator electrodynamics

The first aim of this thesis is to perform a complete THz and IR steady-state study of electrodynamic properties of Bi$_2$Se$_3$ thin films grown on Al$_2$O$_3$ (sapphire) and Si substrates. Light transmittance through the samples has been measured by means of Fourier Transform Infrared (FTIR) Spectroscopy in order to individuate the free carrier surface contributions due to the topological state and the bulk contributions, i.e. the optical phonons and possible further bands due to impurities.

![Figure 1: Extinction coefficient (a) and multicomponent Drude-Lorentz fit (b) for a 60 nm thick Bi$_2$Se$_3$ film grown on sapphire substrate.](image-url)
Extinction coefficient of a 60 nm thick Bi$_2$Se$_3$ film on sapphire is shown in Fig. 1 (a) for maximum and minimum measured temperature. Data have been fitted by means of a Drude-Lorentz model with two oscillators, representing $\alpha$ and $\beta$ phonons of Bi$_2$Se$_3$ bulk [9]. Fit and different component contributions are shown in panel (b) of Fig. 1.

The study of Bi$_2$Se$_3$ on Si will deepen the knowledge of the material since the transmission window of Silicon extends up to the mid-IR range, in contrast with the case of Al$_2$O$_3$. Thin film investigations will be extended on recently discovered CaMnBi$_2$ single crystals which present 3D Dirac carriers at variance with pure 2D showed by Bi$_2$Se$_3$.

3 Plasmonic excitations in the THz range

Surface Plasmons (SPs) are 2-dimension (2D) collective electronic excitations whose interaction with light can be engineered through specific patterning of a metal surface. In particular, SPs of conventional (massive) electrons can be used for different applications ranging from mass sensors, light confinement devices, and optical microscopy beyond the diffraction limit [5]. Recently, a new development in the field of plasmonics has been achieved by means of engineering plasmonic structures in Topological Insulators (TIs). Indeed, their peculiar properties such as 2D intrinsic transport carried out by Dirac fermions, very high surface density, backscattering protection and robustness of the topological phase at room temperature, make them perfect candidates to develop and take further plasmon based technology.

Figure 2: SEM pictures of patterning on Bi$_2$Se$_3$ films taken at IFN in Rome.

We fabricated Bi$_2$Se$_3$-based plasmonic devices, by means of patterning
the samples with several shapes, in order to have THz plasmonic resonances. Two SEM pictures of patterning examples, ribbon arrays and ring arrays, are shown in Fig.2.

The infrared study of Bi$_2$Se$_3$ films patterned with ribbon arrays has been recently performed \[3\] and led to the quantitative identification of the observed resonances with Dirac plasmonic excitations.

In this project we investigated devices patterned with micro-ring arrays, which are interesting because they exhibit two distinct resonances (bonding and antibonding), arising from the hybridization between the resonance of a disk and the one of an anti-dot \[6\]. The measured extinction coefficient has been compared to \textit{ab initio} analytical model for plasmonic resonances, through a collaboration with Prof. De Abajo of the Institute of Photonic Sciences in Barcelona.

The comparison, shown in Fig.3, gives an impressive agreement, given the fact that the model has no free parameter, thus opening the way for further prediction and tailoring of plasmonic devices in the THz range.

4 Magnetoplasmons

Another aim of the project is to study the excitations of Bi$_2$Se$_3$ micro-disk arrays, and to perform transmission measurements under the effect of a strong magnetic field (B up to 30 T) perpendicular to the surface. These measurements beamtime has already been achieved at the Nijmegen High Field Magnet Laboratory in Netherlands. Due to the high B-field we expect to observe and characterize the resonance splitting due to the excitation of magnetoplasmons and edge plasmons whose behavior is strongly related to the topological protection of surface carriers \[8\].

5 Electrostatic gating of surface carriers

A real breakthrough in THz plasmonic technology could be the possibility to tune the resonances by an external input. This could be achieved by engineering a Field Effect Device (FED), by depositing gold electrodes (drain, source, contacts for voltage measurements and gate) on the sample. A first experiment has been done in collaboration with Prof. R. Gonnelli and collaborators at DISAT -Dipartimento Scienza Applicata e Tecnologia, Politecnico di Torino \[7\], but there is still not a sufficient charge injection via gating.

Electrostatic tuning of plasmons on TI-based devices could be also a very important step towards the comprehension of the Dirac nature of carriers on TI surfaces. Indeed, although the presence of Dirac-like fermions has been proved in surface transport, plasmonic excitations cannot be associated only
Figure 3: Extinction data (left) and analytical calculations (right) for four samples of Bi$_2$Se$_3$ micro-ring arrays with different geometrical parameters.
with 2D Dirac charge carriers. A band bending phenomenon due to electrostatic effect at the bulk/edge interface may induce metallic extrinsic states, i.e. a massive transport channel parallel to the intrinsic Dirac channel. The relation between these two different contributions has not been investigated yet and electrostatic gating in order to increase the surface carrier density $n$ could be a resolutive tool to achieve a more complete comprehension. Indeed, the plasmonic dispersion as a function of $n$ is different in the two cases: $n^{1/2}$ for conventional massive fermions and $n^{1/4}$ in case of Dirac fermions.

6 Effect of a Quantum Phase Transition on collective dynamics

Another part of the project is the investigation of the effect of the quantum phase transition (QPT) from a topological insulator to a conventional band insulator on the plasmonic excitations. In order to do that, we studied micro-ribbon arrays of Bi$_{1-x}$In$_x$Se$_3$ ($x=0$, 0.02, 0.03, 0.06, 0.07, 0.1). Under the effect of In-Bi substitution, this material undergoes a QPT around $x=0.05$, as recently observed by means of ARPES [10] and time domain spectroscopy measurements [11]. Measurements have been performed very recently using synchrotron light at BESSY II in Berlin and data are still under analysis. In Fig.4 we show the extinction data at $T=10$ K. As can be seen, the plasmonic resonance centered around 70 cm$^{-1}$ undergoes strong transformation as the In content increases. The study of plasmon dispersion and width as a function of doping represent a first study of the behavior of collective excitations through the QPT.

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7 Pump-probe on Topological Insulators

The steady-state investigation will be extended to non-equilibrium properties by means of pump-probe spectroscopy. Both an apparatus based on a fs laser at the TERALAB laboratory at Rome La Sapienza and on the Free-Electron Laser SPARC at LNF@INFN will be used. The main issues of those investigations concern with the study of the main scattering mechanisms showed by Dirac fermions at the TI interfaces and their intrinsic non-linear behavior due to the mass-less electronic dispersion [4].
Figure 4: Extinction data for Bi$_{1-x}$In$_x$Se$_3$ thin films patterned with micro-ribbon arrays.

References
