Supporting Information for: "Gate-Variable Mid-Infrared Optical Transitions in a $(Bi_{1-x}Sb_x)_2Te_3$ Topological Insulator"

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Epitaxial lift-off methodology:

After spin-coating PMMA (950 A8) onto the surface of the films and baking them on a hot-plate at 170 C for 2 minutes, the chips are placed into a bath of buffered hydrofluoric acid. The film begins peeling off the substrate after 2-3 hours, at which point the chip is placed into a series of DI water baths. The chip is held at the surface of the water, and surface tension is used to complete peeling of the film. The film floats on the surface of the water, and is lifted out with a thermal oxide on silicon chip. This chip is dried overnight, and the PMMA is removed with acetone. This process and a transferred film are shown in Fig. S1.

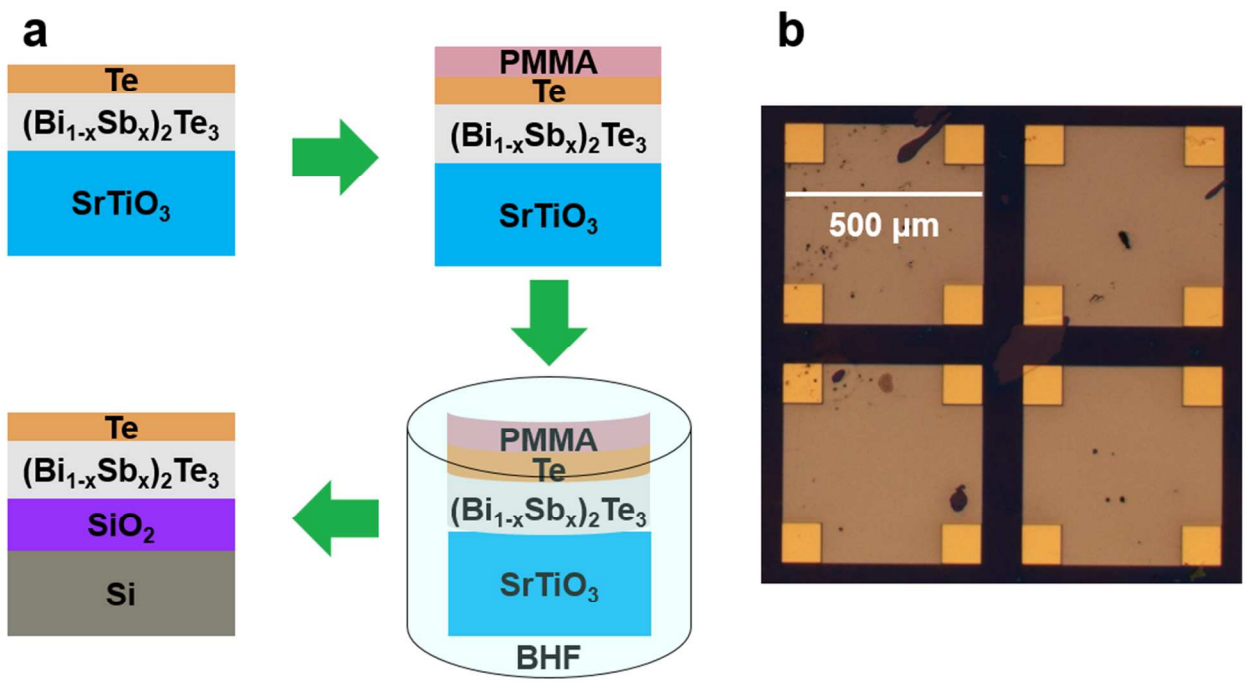

Figure S1: Transfer method and result. **(a)** Outline of transfer process. PMMA is spin-coated onto $(Bi_{1-x}Sb_x)_2Te_3$ film on its STO growth substrate. The sample is then submerged into buffered HF until the PMMA / Te / $(Bi_{1-x}Sb_x)_2Te_3$ stack peels from the STO. The stack is scooped out of water with a SiO_2 / Si chip, dried, and treated with acetone to remove the PMMA. **(a)** Optical microscope image of devices fabricated on a film transferred to SiO_2 / Si.

Low temperature transmittance:

Gate-variable FTIR transmittance is also measured at 5 K, in order to understand the low temperature infrared response of the $(Bi_{1-x}Sb_x)_2Te_3$ film and look for TSS to TSS interband transitions. These measurements are performed in a modified Oxford cryostat using a Bruker Lumos infrared microscope and spectrometer, in the Basov Lab facilities at UCSD. The behavior seen – shown in Fig. S2 – is consistent with that seen at 78 K, with a smaller Fermi-Dirac distribution width. An additional kink feature is seen near six microns, but no clear evidence of TSS to TSS interband transitions – which should show a universal optical conductivity of $\pi e^2/8h$ above $2E_F$ – is seen.[1] The persistence of bulk-related modulation at high gate voltage and low temperature indicates that some band bending is likely present. The presence of accumulating ice dampens the modulation around a narrow feature at three microns.[2]

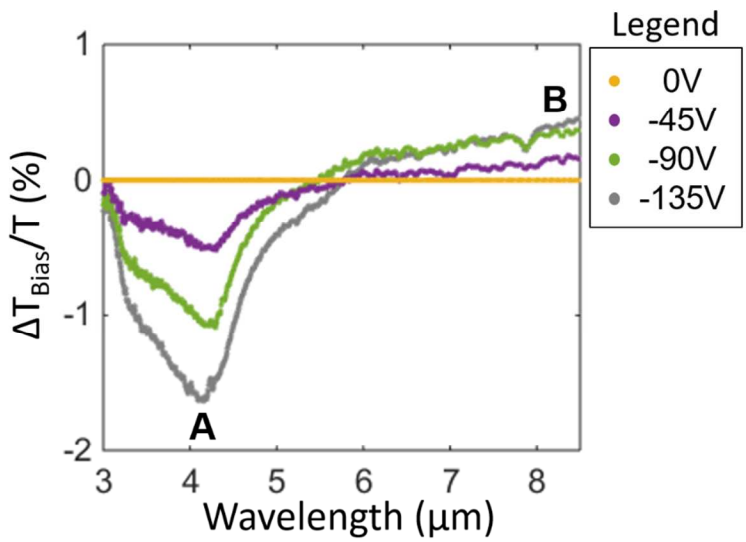

Figure S2: Gate-variable FTIR transmittance at T = 5 K. Transmittance is shown normalized to zero bias case, as the Fermi level is pushed into the bulk band gap and towards the Dirac point. Similar behavior is seen as in T = 78 K, with two main differences. The band-edge Pauli-blocking effect is sharper and more pronounced, likely due to narrowing of the Fermi-Dirac distribution of carrier energies. There also appears a kink feature in transmittance near 6 microns. This feature may be related, but no clear evidence of TSS to TSS interband transitions is observed.

Room temperature transmittance and reflectance:

Gate-variable FTIR transmittance and reflectance are also measured at 300 K, in order to understand how the infrared response of the $(Bi_{1-x}Sb_x)_2Te_3$ film varies with temperature and demonstrate the possibility of room temperature optical modulation. These measurements are performed in the same configuration as the 78 K measurements. The behavior seen, shown in Fig. S3 – is consistent with that seen in the 78 K measurements, but show less modulation.

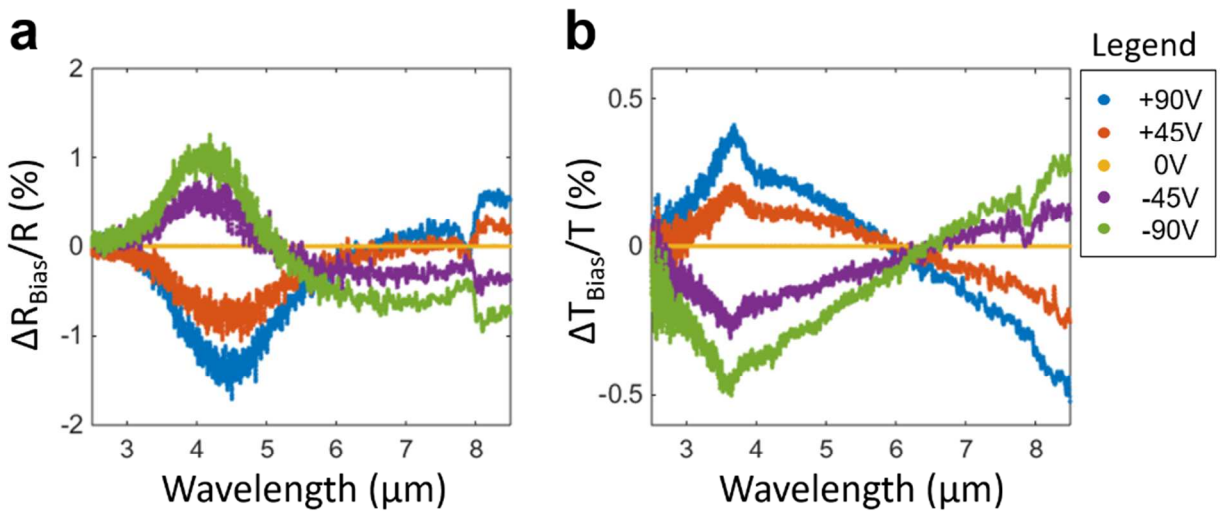

Figure S3: Room temperature FTIR spectra. **(a)** Gate-variable FTIR transmittance, shown normalized to the zero bias case. **(b)** Gate-variable FTIR reflectance, shown normalized to the zero bias case. Similar behavior is seen as with 78 K measurements, but with a smaller modulation depth.

Thomas-Fermi model of screening:

The screening of the gate-induced potential in the $(Bi_{1-x}Sb_x)_2Te_3$ film is complex, due to the interaction of charges in the two conductive surfaces and bulk. For a simple estimate of the characteristic screening length, we use a Thomas-Fermi model of screening in the bulk that has been applied to other layered semiconductors.[3, 4] The voltage drop across a film of thickness D is modelled by Castellanos-Gomez, et al[3], as follows.

$$\Delta V = 2A_0\sigma_0\sqrt{2\beta_0 d}\,\frac{1-r_D}{\sqrt{1-r_D^2}}$$

Here $A_0 = \pi\hbar^2/2m_{||}$ and $\beta_0 = e^2/4e_0k_\perp A_0$ are constants, $r_D = \sigma(D)/\sigma(0)$, and σ_0, d and $k_\perp$ are the gate-induced areal charge, interlayer spacing and out-of-plane dielectric constant, respectively. Using an in-plane effective mass $m_{||} = 0.054$[5], out of plane dielectric constant $k_\perp = 168$[6] and the areal charge due to a +/- 90 V applied bias, we find that the voltage drop falls by a factor of e over a screening length of 10 nm.

References:

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