

Lateral photovoltaic effect in $\text{SiO}_2/\text{TeO}_2/\text{Bi}_2\text{Te}_3/\text{n-Si}$ structure

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Abstract

The lateral photovoltaic effect (LPE) in a $\text{SiO}_2/\text{TeO}_2/\text{Bi}_2\text{Te}_3/\text{n-Si}$ hybrid heterostructure was investigated as a function of light wavelength, temperature, illumination position, and magnetic field. The Schottky barrier height of the structure was estimated to be $\Phi_B = 0.3$ eV using the thermionic emission model. A pronounced change in the LPE is observed near $\lambda = 1$ μm , including a reversal of the photovoltage polarity. This indicates the transition between two dominant photovoltaic channels associated with carrier photogeneration in the Si substrate and Bi_2Te_3 film. The Si-related contribution was found to be sensitive to the magnetic field, whereas the Bi_2Te_3 -related contribution remains nearly unaffected. The magnetic-field effect on the Si-related LPE is attributed to interface states localized near the $\text{Bi}_2\text{Te}_3/\text{n-Si}$ interface. These results demonstrate the coexistence of distinct photovoltaic channels in $\text{Bi}_2\text{Te}_3/\text{Si}$ -based hybrid structures and provide insight into the mechanisms governing their photoelectric and magnetically sensitive response.

Introduction

Recent advances in optoelectronics have been driven by the development of materials that combine high optical sensitivity, broad spectral absorption, and suitable electronic and magnetic properties for applications in photodetectors, hybrid sensors, and spintronic devices. Among such materials, Bi_2Te_3 has attracted considerable attention as a topological insulator characterized by high electrical conductivity, low thermal conductivity, and a narrow bandgap ($\sim 0.15\text{--}0.2$ eV), enabling sensitivity in the mid-infrared to near-infrared spectral range [1, 2]. Importantly, Bi_2Te_3 retains its thermoelectric and topological properties when grown on silicon substrates, particularly under optimized tellurium growth conditions [3]. Integration of Bi_2Te_3 with Si is especially promising for compatibility with silicon microelectronics and on-chip energy conversion technologies [4].

Investigation of hybrid structures based on Bi_2Te_3 and Si, particularly their photovoltaic response, can provide insight into the mechanisms of the photovoltaic effect in a broad spectral range. In particular, the lateral photovoltaic effect (LPE) has attracted significant attention due to both its fundamental importance and its technological applications [5–7]. Since the output signal directly reflects the position of the incident light spot, LPE is widely utilized in position-sensitive detectors and optical sensing systems [8–10]. Furthermore, LPE-based devices are relevant for applications in microscale and nanoscale sensing, surface characterization, and optoelectronic systems [11–14].

In this work, we investigate the lateral photovoltage in a $\text{SiO}_2/\text{TeO}_2/\text{Bi}_2\text{Te}_3/\text{n-Si}$ heterostructure, focusing on its spectral, temperature-dependent, and magnetic-field-dependent behavior. The results provide insight into the mechanisms governing the photovoltaic response in such hybrid systems and suggest possible approaches for controlling electronic and magnetic transport via optical excitation.

Experimental details

Bi₂Te₃ thin films were grown by molecular beam epitaxy (MBE) under ultrahigh vacuum conditions with a base pressure of 5.0×10^{-10} Torr. The substrates were n-type Si(111) wafers, doped with phosphorus ($N_D \sim 10^{14} \text{ cm}^{-3}$), with dimensions of $3 \times 6 \times 0.5 \text{ mm}^3$. Prior to growth, the substrates were degassed at 600°C for 6 hours and subsequently flash-annealed up to 1280°C to obtain a clean Si(111) 7×7 surface.

Bismuth and tellurium were evaporated from effusion cells. A 10 nm Bi₂Te₃ layer was deposited at 240°C under Te-rich conditions, with a Bi:Te flux ratio of 1:14 to suppress tellurium vacancies. The growth rate was approximately 0.3 quintuple layers (QL) per minute (1 QL $\approx$ 1 nm) [15]. After deposition, the samples were cooled to room temperature and capped with 2 nm of Te and 1 nm of amorphous Si to prevent oxidation. Upon exposure to air, these layers formed native oxides (SiO₂ and TeO₂) resulting in a transparent protective cap [16].

A rectangular sample ($3 \times 6 \text{ mm}^2$) was prepared for electrical measurements. Lateral photovoltage (LPV) was measured using surface contacts formed on the top of the film (Fig. 2(a)) with silver epoxy, separated by approximately 5 mm. Illumination was provided by a halogen lamp coupled to a monochromator, allowing wavelength variation in the range of 0.4–3 μm with an incident power of approximately 1.5 mW. A narrow rectangular illumination strip ($\sim 0.5 \text{ mm}$) was positioned near one pair of contacts. For position-sensitive measurements, illumination was applied as a spot ($\sim 1 \text{ mm}^2$).

Results and discussion

The Schottky barrier height of the SiO₂/TeO₂/Bi₂Te₃/n-Si structure was determined using the thermionic emission model [17]. Figure 1 (a) shows I - V - T characteristics measured between the top film contact and the bottom substrate contact. According to thermionic emission theory, the diode saturation current is related to the Schottky barrier height by:

$$I_S = AA^*T^2 e^{-\frac{q\Phi_B}{kT}},$$

1

where A^* is the Richardson's constant for the semiconductor, A is the diode area. By plotting I_s/T^2 in Arrhenius coordinates (Fig. 1 (b)), Φ_B can be extracted from the slope of the linear fit. The estimated barrier height for the sample was found to be $\Phi_B = 0.3 \text{ eV}$ which is consistent with previously reported values for Bi-based heterojunctions [18, 19].

Figure 2(a) shows the schematic for measuring LPV. The dependences of LPV on the light spot position measured at room temperature (Fig. 1(b)) are typical for such systems [20, 21]. When the light spot is placed in the middle between the contacts ($x = 0$), the LPV value is zero due to the symmetry of carrier diffusion of the carriers. The reversal of the LPV sign with the sign of x occurs because the electrode with the higher concentration of photogenerated carriers changes its polarity as the illumination position is shifted across the center of the sample. The maximum LPV values are observed when a light spot is

positioned in the middle between the center and one of the contacts. All of the measurements below were performed with light spot positioned near the LPV maximum.

The spectral dependence of LPV, normalized to the incident power, exhibits pronounced changes near a wavelength of approximately 1 μm , including a reversal in the sign of the photovoltage (Fig. 3). This behavior can be understood by considering the bandgap energies of the constituent layers of the structure. Silicon has a bandgap of approximately 1.12 eV [22], corresponding to a cutoff wavelength near 1.1 μm , whereas Bi_2Te_3 exhibits a much smaller bandgap (~ 0.17 eV) [23], corresponding to infrared absorption up to ~ 7.3 μm . The maximum absorption wavelength is defined using the expression:

$$\lambda_{\text{max}} = \frac{hc}{E_g} \quad (2),$$

where E_g is the bandgap of the corresponding material.

Thus, optical absorption in silicon becomes negligible for wavelengths exceeding ~ 1.1 μm , while Bi_2Te_3 continues to absorb light in this region. The observed inflection point in the $\text{LPV}(\lambda)$ curves is therefore attributed to a transition between two dominant photovoltaic channels: one associated with the Si substrate and the other with the Bi_2Te_3 film. Minor contributions from the oxide layers cannot be completely excluded; however, they are expected to be negligible because of the small thickness of the oxide films. The slight discrepancy between the observed inflection wavelength (1 μm) and the intrinsic cutoff wavelength of Si (1.1 μm) may be attributed to the spectral dispersion of the lamp as well as to the temperature-induced variation of the Si band gap at cryogenic temperatures.

The LPV spectrum can be divided into two regions: (i) a short-wavelength region where both Si and Bi_2Te_3 contribute to photovoltage generation, and (ii) a long-wavelength region where only the Bi_2Te_3 channel remains active. The reversal of LPV sign indicates that the dominant carrier types contributing to the photovoltage differ between these channels. Measurements of $\text{LPV}(\lambda)$ curves at different temperatures reveal that the substrate-related contribution exhibits stronger temperature dependence than the film-related contribution, with a pronounced maxima near $T \approx 30$ K.

Analysis of $\text{LPV}(T)$ curves shows distinct features at different wavelengths (Fig. 4). At $\lambda = 1.2$ μm , a negative photovoltage peak is observed, which is attributed to the Bi_2Te_3 film. These observations further support the presence of two independent photovoltaic channels. LPV below 25 K is observed only at $\lambda = 0.85$ μm and $\lambda = 1.2$ μm . Distinct LPV maxima are observed at $T \approx 30\text{--}35$ K, which is consistent with spectral dependences (Fig. 3(a)). The absence of a measurable signal in the dark confirms that thermoelectric effects are negligible in the investigated temperature range.

Magnetic-field-dependent measurements performed near the temperatures corresponding to LPV maxima (Fig. 5) indicate that the substrate-related contribution (red) is sensitive to magnetic field, whereas the film-related (blue) contribution remains largely unaffected. This suggests that the two

channels are governed by different physical mechanisms, one of which exhibits magnetic-field sensitivity.

The observed LPV maxima and their dependence on magnetic field are attributed to surface states localized near the $\text{Bi}_2\text{Te}_3/\text{n-Si}$ interface. Similar states in the same temperature range were previously observed in our studies of charge transport in $\text{Me}/\text{SiO}_2/\text{Si}$ structures and were confirmed by impedance spectroscopy measurements [24, 25]. These states likely originate from energy levels formed in the band gap of silicon by standard boron/phosphorus dopants or impurities, which diffuse into silicon at the film growth stage. These levels are located in the space-charge region and participate in carrier trapping and emission processes [26, 27]. Application of a magnetic field rises the energy levels of these states, thereby reducing their contribution to the LPV signal and leading to a decrease in its amplitude [28].

Conclusion

The lateral photovoltaic effect in $\text{SiO}_2/\text{TeO}_2/\text{Bi}_2\text{Te}_3/\text{n-Si}$ heterostructures was investigated as a function of wavelength, temperature, light spot position, and magnetic field. The estimated barrier height for the sample was $\Phi_B = 0.3$ eV, which falls within the range of reported values for Bi-based heterojunctions. The positional dependences of LPV showed the typical behavior, confirming the efficient separation of electron-hole pairs and diffusion of photogenerated carriers within the structure. Spectral and temperature dependences of LPV revealed a pronounced change in LPV behavior near $\lambda \approx 1$ μm , including a reversal of the photovoltage sign. This effect was attributed to the transition between two dominant photovoltaic channels associated with the Si substrate and the Bi_2Te_3 film with different dominant carrier types contributing to the photovoltaic response in these channels. The absence of a measurable signal in the dark excludes influence of thermoelectric effects on observed LPV signals in the investigated temperature range.

Magnetic-field measurements revealed that the substrate-related photovoltaic channel is sensitive to magnetic field, while the Bi_2Te_3 -related contribution remains nearly unchanged. The magnetic-field-dependent LPV maxima below 40 K were attributed to the surface states localized near the $\text{Bi}_2\text{Te}_3/\text{n-Si}$ interface and associated with impurity levels in the phosphorus-doped Si substrate.

The obtained results demonstrate that $\text{SiO}_2/\text{TeO}_2/\text{Bi}_2\text{Te}_3/\text{n-Si}$ structures possess multiple photovoltaic channels with distinct spectral and magnetic characteristics. These findings provide deeper insight into the mechanisms governing photovoltaic transport in hybrid topological insulator/semiconductor systems and indicate their potential for applications in optoelectronic and position-sensitive devices.

Declarations

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Author Contribution

I.A. Bondarev: writing – original draft, investigation, methodology. M.V. Rautskii: methodology, review and editing. A.S. Tarasov: supervision, review and editing. T.A. Pisarenko: supervision, data interpretation. A.A. Yakovlev: investigation. V.V. Mararov: sample preparation. D.A. Tsukanov: data interpretation.

Data availability statement

Data are available from the corresponding author on reasonable request.

Ethics - Conflict of interest

The authors have no competing interests as defined by Springer, or other interests that might be perceived to influence the results and/or discussion reported in this paper.

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Figures

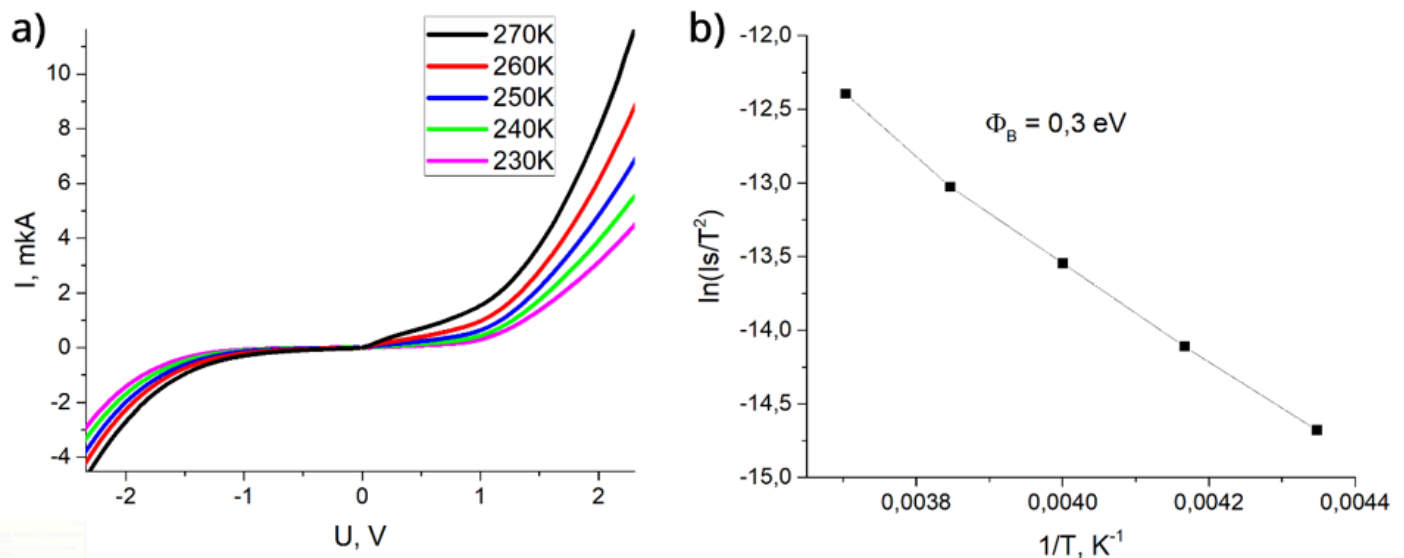


Figure 1

a) *I-V* characteristics of the SiO₂/TeO₂/Bi₂Te₃/n-Si Schottky diode at different T. b) $\ln(I/T^2)$ vs $1/T$ plot for estimating Schottky height.

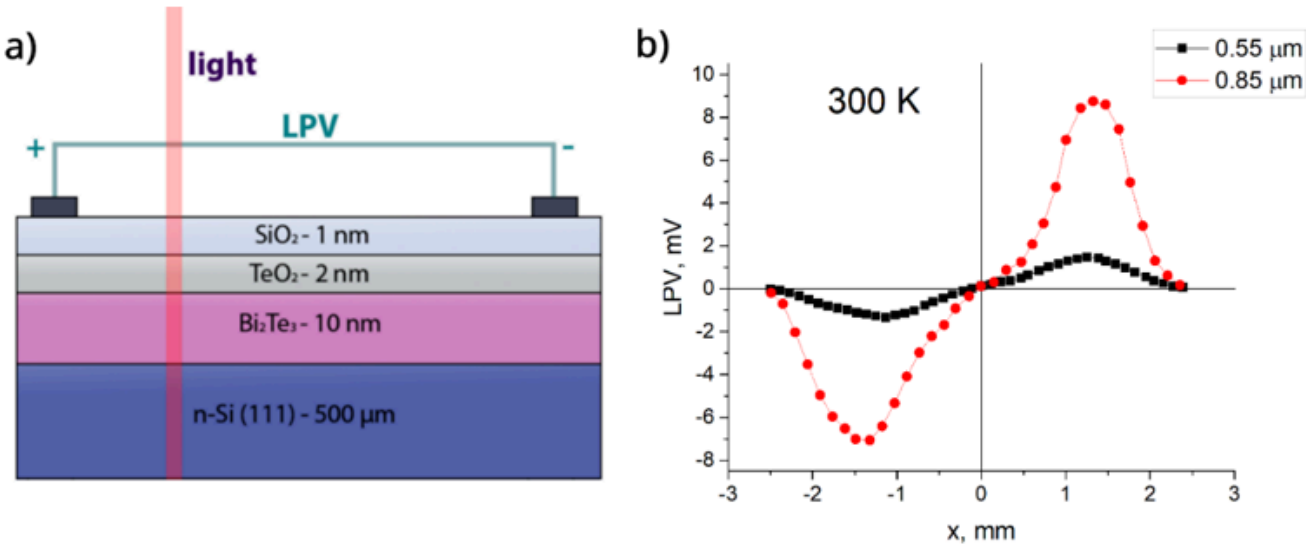


Figure 2

a) Schematics of LPV measurement in SiO₂/TeO₂/Bi₂Te₃/n-Si. b) LPV as function of laser position, where $x = 0$ is the center between contacts.

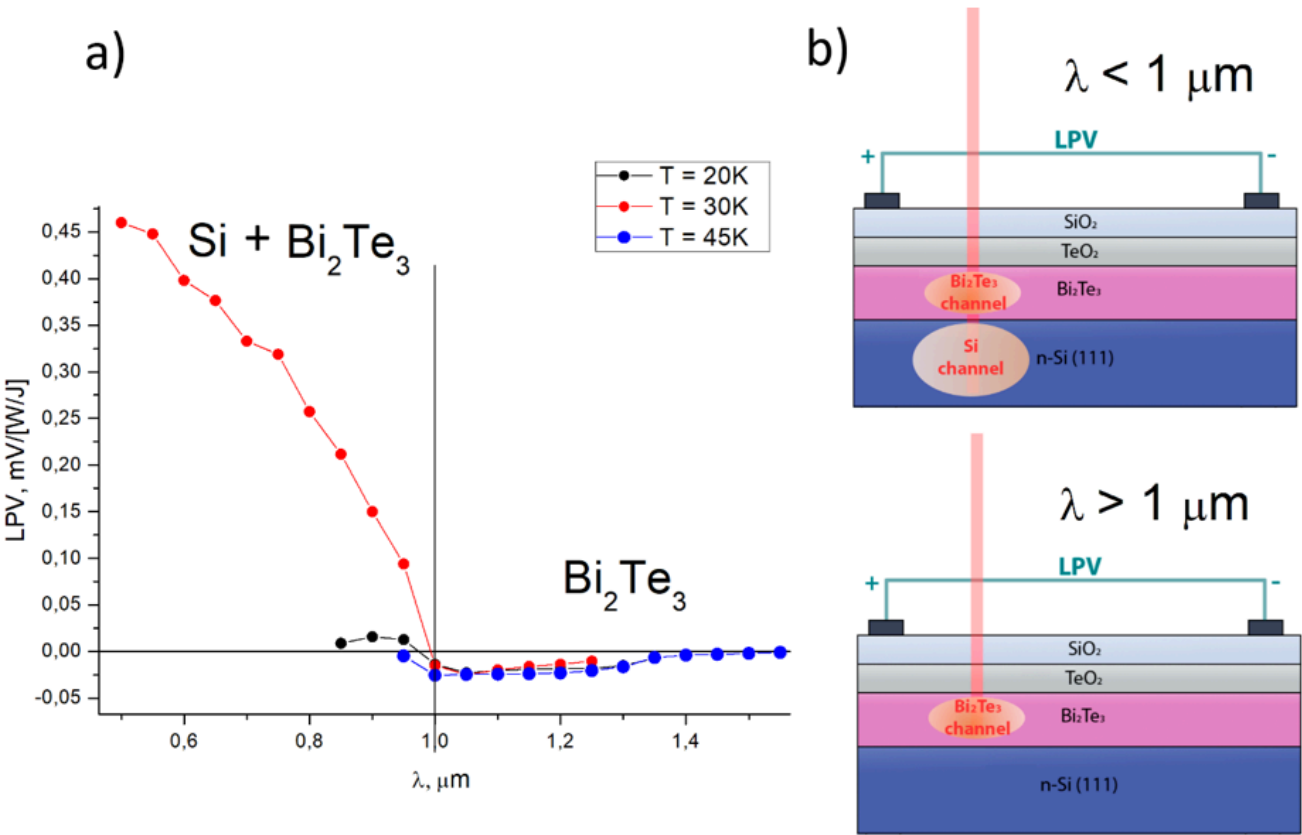


Figure 3

a) LPV as a function of wavelength at $T = 20;30;45\text{K}$. b) scheme of transition between absorption channels between Si and Bi_2Te_3 .

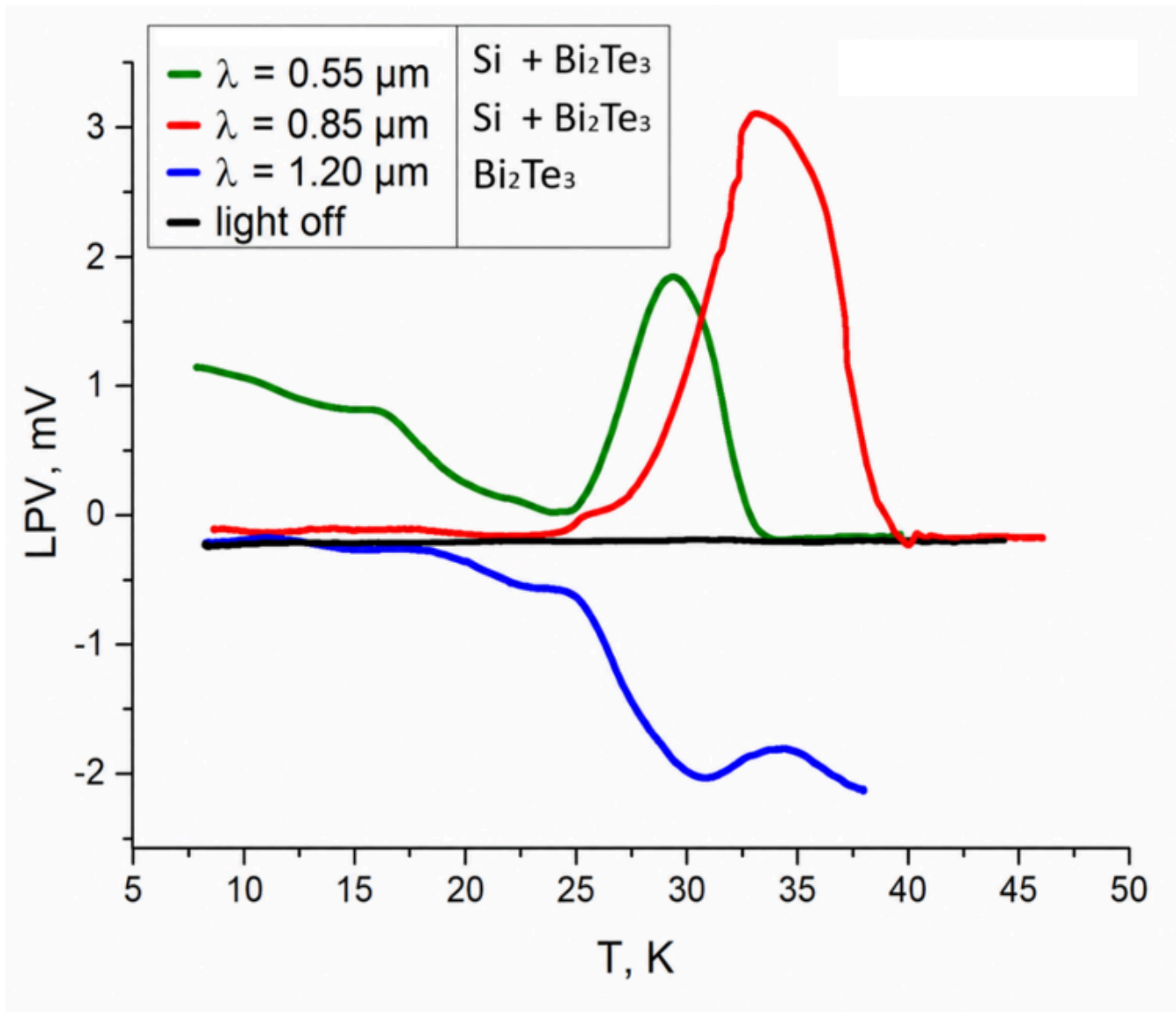


Figure 4

LPV as function of temperature at different values of λ and in the dark.

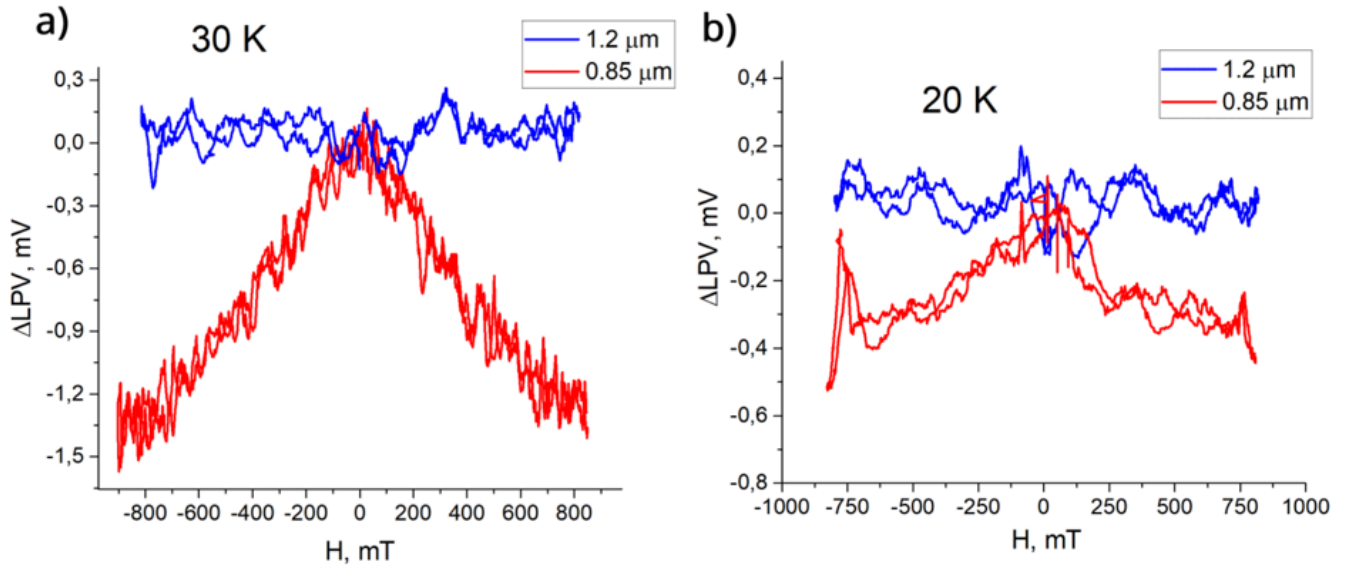


Figure 5

LPV as function of magnetic field at $T = 30$ K (a) and 20 K (b) for Si (red) and Bi_2Te_3 (blue) dominant channels.