Circular photocurrent measurements are a promising new approach for spin-optoelectronics. To date, such currents have only been induced in topological insulator flakes or extended films. It is not clear whether they can be generated in nanodevices. In this paper, we demonstrate the generation of circular photocurrents in Bi$_2$Se$_3$ nanowires. Each nanowire shows topological surface states. Here, we generate and distinguish the different photocurrent contributions via the driving light wave. We separate the circular photocurrents from those due to thermal Seebeck effects, through controlling the laser light polarization. The results reveal a spin-polarized surface-Dirac electron flow in the nanowires arising from spin-momentum locking and spin-orbit effects. The second photocurrent contribution described in this letter is caused by the thermal Seebeck effect. By scanning the photocurrent, it can be spatially resolved; upon reversing the gradient direction along the nanowire, the photocurrent changes its sign, and close to the gold contacts, the amplitudes of the different photocurrent contributions are affected by the proximity to the contacts. In the center of the nanowires, where the effects from the gold contact/ topological insulator stacks vanish, the spin-polarized current remains constant along the nanowires. This opens up a new method of all-optical spin current generation in topological insulator nanowires and hybrid structures for nanoscale spin-orbitronics.

Keywords: topological insulator, photocurrent, nanowire, circular photocgalvanic effect, Seebeck effect
Photocurrent measurements in topological insulator Bi$_2$Se$_3$ nanowires

The Bi$_2$Se$_3$ nanowires were synthesized by Au-catalyzed vapor-liquid-solid method on a Si(111) substrate (as described here[12]). The cross-section of the nanowires is either rectangular or trapezoidal, resulting from the layered crystal structure. The width of the nanowires is on the scale of 50 nm and the thickness is in the range of 50 nm – 150 nm. The length can be as long as several tens of micrometers. The nanowire presented in FIG. 2 (a) has a total length of 36 µm. The Bi$_2$Se$_3$ nanowires are grown in the [110] direction as a single-crystal structure and have a smooth surface. The chemical composition can be characterized by an energy dispersive spectrometer in the scanning TEM mode. The measured ratio is 2:3 as expected for Bi$_2$Se$_3$. The grown nanowires are mechanically transferred onto a Si (111) substrate, and the gold contacts separated by a 14 µm gap are fabricated on top of the nanowire by lithography. FIG. 2 (a) shows a micrograph of one of the nanowire devices with two contacts, which are each connected to two gold pads on the left- and on the right-hand sides of the nanowire[13]. The sample is mounted with silver paste onto a chip carrier and connected with 25 nm diameter gold wires by wire bonding. The light source for the photocurrent measurements is a diode laser with a wavelength of 785 nm (1.55 eV) modulated at a frequency of 77 Hz. The laser light passes through a linear polarizer and a quarter-wave plate (qwp) prior to impinging on the sample surface under an angle of incidence of 45°. The rotation angle $\alpha$ of the qwp is controlled by a step motor to change the polarization of the excitation beam. The laser light is focused down to $(4.3 \pm 0.11) \mu$m $\times (2.89 \pm 0.08) \mu$m on the sample surface. The intensity of the light reflected from the sample surface is measured by a photodiode. The photocurrent between the two contacts and the light reflected from the sample surface are simultaneously measured by a lock-in amplifier. The laser spot can be moved across the sample surface along the vertical and horizontal directions by two step motors with a minimum step size smaller than 1 µm with an error of 200 nm. The raster pattern of the laser spot (red dots) is depicted in FIG. 1(b), as drawn on a light microscopy image of the sample. The measurement starts with the laser spot in the right upper corner (position 1 in FIG. 1(b)). Then the qwp is rotated by $\Delta \alpha = 6^\circ$ steps to carry out a full rotation while the photovoltage and the intensity of the reflected beam are measured. Afterwards, the laser spot is moved to the next position according to the raster pattern in FIG. 1(b), repeating the measurement procedure until the bottom left position is reached.

For each data point in the two-dimensional voltage
Photocurrent measurements in topological insulator Bi\textsubscript{2}Se\textsubscript{3} nanowires

In the reflectivity map (FIG. 2 (b)) three different areas can be distinguished. The area with the highest intensity (white) shows the position of the Au contacts, while the region with the lowest reflectivity (black) represents the 300 nm SiO on top of the Si substrate. The nanowire can be clearly distinguished between the contacts (in dark gray). Its size looks exaggerated since its diameter (150 nm) is smaller than the spot size of the laser beam, so it acts as a scattering center. Therefore, the reflectivity map proves that the area shown in FIG. 2 (a) is illuminated and indicates the position of the nanowire. The nanowire is marked in the photovoltage maps (FIG. 3) by a black line.

The three selected photovoltage measurements in FIG. 3 at three different positions along the nanowire (marked in blue in FIG. 2 (b)) show good agreement between Eq. (1) and the measured voltage. It is also observed, that the thermoelectric contribution D, which is equal to the shift along the vertical direction, is at least one order of magnitude larger than the spin-polarized contribution C. The spatially resolved maps in FIG. 4 enable a more detailed inspection of the two contributions. The thermoelectric amplitude D (FIG. 4(a)) changes its sign from positive at the top electrode to negative at the lower electrode. Note that the thermoelectric current that creates the thermoelectric voltage is generated by two temperature gradients with opposite signs that point from the laser spot position towards the two colder contacts. Therefore, the position of the laser spot with respect to the contacts determines the size and sign of the thermoelectric voltage. When the laser spot is in the center between the contacts, the two temperature gradients cancel, and thus, the net temperature gradient and D vanish. In our measurements (FIG. 4(a)), the direction of the net temperature gradient is encoded in red and blue, corresponding to the gradients pointing towards the lower or upper contacts, respectively. At the vertical position of 13 μm in FIG. 4(a), the thermoelectric contribution D becomes zero. Once the laser spot is moved toward one of the electrodes, the net temperature gradient is non-zero, and a net current is generated by the Seebeck effect. The sign of the thermoelectric current changes from top to bottom since the direction of the net temperature gradient is reversed. Thus, the voltage of the contour plot in the vertical direction along the nanowire changes its sign.

\begin{align*}
\text{Photovoltage } v(\alpha) &= C \sin(2\alpha) + L_1 \sin(4\alpha) + L_2 \cos(4\alpha) + D. \quad (1)
\end{align*}

The contributions can be distinguished by their dependence on the polarization of the exciting laser light. Eq. (1) has previously been introduced to separate the different contributions to photocurrent measurements in exfoliated Bi\textsubscript{2}Se\textsubscript{3} Hall bar devices. The first term $C \sin(2\alpha)$ describes the amount of spin-polarized voltage generated by the circular photogalvanic effect since it modulates the difference in the photovoltage for left and right circular polarized light and is zero if the exciting light is linear polarized. In the following, the magnitude of the amplitude C, which is half of the difference between the photovoltage for different helicities (see Fig. 3), is used as a measure for the size of the spin-polarized voltage. The second term $L_1 \sin(4\alpha)$ and third term $L_2 \cos(4\alpha)$ describe the contributions that arise from the linear photogalvanic effect and the photon drag effect. The last term D is independent of the polarization and arises from the Seebeck effect. Since the laser spot is smaller than the distance between the gold contacts, it creates an overall temperature gradient that can change in direction and size as the laser spot is moved across the sample surface. The measured photovoltage is analyzed by Eq. (1) to separate the four contributions at every laser spot position. The horizontal and vertical positions of the laser spot are then used as the spatial coordinates for the extracted amplitudes as in FIG. 4 for the thermoelectric contribution represented by D and the spin-polarized contribution represented by C. At the same time, the intensity of the reflected light for every value of the photovoltage is measured with a second lock-in amplifier. Instead of fitting Eq. (1) to the obtained values, we take the value for a fixed polarization at $\alpha = 0^\circ$ and again use the position of the laser spot as the coordinates for the reflectivity to obtain a two-dimensional map of the reflectivity (see FIG. 2 (b)) which allows us to identify the positions of the nanowires and the gold contacts.
A slight enhancement of the voltage is observed when not only the nanowire but also the nanowire underneath the gold contact is partially illuminated. This appears for the vertical positions above 22 µm and below 11 µm and is manifested by the nonlinear increase of the photovoltage in the vertical contour plot and also by the circular shape of the lines in the 2D map in FIG. 4 (a). This effect is also observed for measurements of GaN, ZnO and Si nanowires. In these materials, the observed increase is a result of the Schottky effect [19][21]. In our case, the gold contact is metallic and the TI can act as a semiconducting layer. The sign of the current caused by the band bending at the metal/semiconductor interface changes between the contacts since the band bending is symmetrical with regard to the center of the nanowire; this is in good agreement with the behavior of the thermoelectric voltage D observed in this work.

To exclude the influence of the contacts, we focus on the spin-polarized contribution C in this work in the area between 15 and 20 µm along the vertical axes displayed in FIG. 4 (b) in green. The contour plots along the horizontal direction show that the spin-polarized voltage C decreases when the center of the laser spot does not match the position of the nanowire at the horizontal position of 13 µm. This proves that the substrate does not contribute to the spin-polarized voltage. The largest value with a modulus of 0.5 µV is reached when the laser spot center matches the nanowire, which is a factor of 80 smaller than the largest value for the thermoelectric contribution $D = 40 \mu V$. The largest values are reached on the small plateau shown in the vertical contour plot over a range of 4 µm. Closer to the contacts, the spin-polarized voltage decreases.

In summary, we performed photocurrent measurements on Bi$_2$Se$_3$ nanowires and analyzed the spatially resolved results for the spin-polarized and thermoelectric contributions. For the thermoelectric contribution, we observe a sign change of D along and on the nanowire. In addition, we detect an enhancement of the thermoelectric and the spin-polarized contribution when the nanowire underneath the gold contacts is illuminated in comparison to illuminating only the TI. We also show that spin-polarized currents can be generated in nanowires within the range of 5 µm along the nanowire by using circular polarized light.

Thus, we have demonstrated the ability to drive photo-galvanic currents in nanowires, which shows their promising potential for use in photo-spintronics applications in the future.

We are grateful to the German Science Foundation (DFG) for financial support through the priority program SPP1666: ‘Topological insulators: materials, fundamental properties, devices’ (MU1780/10-2).

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