Voltage control of the quantum scattering time in InAs/GaSb/InAs trilayer quantum wells

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Abstract

We study the evolution of the quantum scattering time by gate voltage training in the topological insulator (TI) based on InAs/GaSb/InAs trilayer quantum wells. Depending on the minimal gate voltage applied during a gate voltage sweep cycle, the quantum scattering time can be improved by 50% from 0.08 ps to 0.12 ps albeit the transport scattering time is rather constant around 1.0 ps. The ratio of the quantum scattering time versus transport scattering time scales linearly with the voltage applied during a gate voltage sweep cycle, the quantum scattering time can be improved by 50% from 0.08 ps to 0.12 ps albeit the transport scattering time is rather constant around 1.0 ps. The ratio of the quantum scattering time versus transport scattering time scales linearly with the charge carrier density and varies from 10 to 30, indicating Coulombic scattering as the dominant scattering mechanism. Our findings may enable to improve bulk and edge properties of TIs based on InAs/GaSb quantum well heterostructures solely by means of an electric field rather than temperature which opens the paths towards their application for macroscopic devices.

1. Introduction

InAs/GaSb bilayer quantum wells (BQWs) are two dimensional topological insulators where the electron and hole gases are spatially separated in the InAs- and GaSb-layers, respectively [1]. Thus, in contrast to the prototypal TI based on HgTe/CdTe quantum wells, a tuning between a trivial and topological phase by a dual gating approach in InAs/GaSb BQWs makes the material system interesting for potential device applications [2] such as topological transistors. However, despite extensive studies on InAs/GaSb BQWs and indications for helical edge transport a fully convincing demonstration of these helical edge states is still elusive [3–9]. By adding another InAs-layer to the BQW, a symmetrical InAs/GaSb/InAs trilayer quantum well (TQW) can be formed [10–12]. Dependent on the individual quantum well thicknesses, a rich phase diagram emerges with either direct or indirect inverted band gaps, gapless phases (semi metallic) or massless Dirac fermions etc [11, 13]. TQWs enable significantly higher band gap energies (up to 60 meV for highly strained quantum wells) enabling higher temperature operation with reduced bulk conductivity [14]. However, even for large-gap TIs in other material systems, e.g. WTe₂ (|Egap| = 100 meV), the conductance quantization could only be seen for channels of a few hundred nm [15]. Also, in the prototypal material system for TIs, HgTe/CdTe QWs helical edge transport could only be observed for channels of a few μm length [16]. This is mainly caused by scattering at small charged islands [17, 18] formed by charged defects in the sample. These defects found in HgTe/CdTe and InAs/GaSb based TIs severely limit their use in potential devices. Lunkzer et al however introduced a new measurement technique to overcome this bottleneck [19]. By sweeping the top-gate voltage to certain negative values and back, they showed that the gap conductance in the topological insulating gap could be increased for the optimal sweeping length. In addition, the scattering length increases to 175 μm. These improvements were assigned to a flattening of the potential landscape in the gap region by this gate-training method.

In this work, we address this bottleneck in InAs/GaSb/InAs trilayer quantum wells by quantitatively studying the evolution of the quantum scattering time $\tau_\text{q}$ by gate-voltage training. By sweeping the top gate...
from a maximum value $V_{\text{max}}$ to a minimum value $V_{\text{min}}$, we observe a hysteresis in the longitudinal resistance $R_{xx}$. Sweeps performed at low magnetic fields provide a distinct difference between the two hysteresis loops, where the amplitude of the Shubnikov–de Haas (SdH) oscillations increases. This is due to a change in the quantum scattering time for both sweeping directions. We investigate this with another experiment in which we change the gate sweeping length and observe a significant increase in the quantum scattering time whereas the transport scattering times remains constant. Furthermore, the ratio of $\tau_q$ and the transport scattering time $\tau_t$ allows us to determine the dominant scattering process.

2. Experimental details and measurement procedure

For our experiments, we used an InAs/GaSb/InAs TQW (10/7/10 nm) with an indirect inverted gap of around $E_{\text{gap}} = 4$ meV. Hall bars of constant width $W = 20 \, \mu m$ but different lengths $L = 20, 40, 60$ and $80 \, \mu m$ (labeled S20, S40, S60 and S80, respectively) were processed. The sample has a relatively small (indirect) band gap of 4 meV that opens between two electron-like levels (at $k_x = k_y = 0$). Dependent on the quantum well thicknesses a large variety of band gap energies (direct and indirect) as well as gapless (Dirac and semimetal) can be obtained [13]. For further information on the growth and processing details see [20]. All measurements were conducted at a temperature of $T = 4.2$ K in the dark. In figure 1(a) $R_{xx}$ as a function of the gate voltage $V_{\text{TG}}$ is shown for sample S60. During the gate voltage sweep, the magnetic field value was set constant to $B = 3$ T. The voltage sweep is performed by starting from the maximal voltage $V_{\text{max}} = +10$ V down to the minimal gate voltage $V_{\text{min}} = -10$ V (down-sweep, colored in red). Afterwards, the sweep direction changes and the gate voltage is increased back to $V_{\text{max}}$ (up-sweep, colored in black). For both sweep directions, a resistance peak ($V_{\text{CNP,up}}$ for the up-sweep and $V_{\text{CNP,down}}$ for the down-sweep) is visible when the Fermi energy is located in the gap region. For higher $V_{\text{TG}}$, the Fermi energy lies in the conduction band and for lower $V_{\text{TG}}$ it is in the valence band. Two prominent differences between the two sweep directions can be identified. First, the gate voltage of the gap region differs by a voltage difference $\Delta V$ between the up- and the down-sweep. This hysteresis occurs probably due to charge accumulation at the interface between the gate dielectric and the semiconductor [21, 22]. Second, a prominent difference between the up- and down-sweep in the amplitude of the SdH-oscillations can be identified. Figure 1(b) shows this in more detail. Here, the oscillations for the up- and down-sweep are depicted. In the graph, the voltage values are normalized to the charge neutrality point (CNP), $V_{\text{TG,CNP}}$, and the longitudinal resistance is displayed by subtracting the baseline resistance $R_{xx,\text{base}}$. The down-sweep oscillation (red) has amplitudes around $\Delta R_{xx,\text{down}} = 20–60 \, \Omega$, whereas the values for the up-sweep (black) are $\Delta R_{xx,\text{up}} = 60–100 \, \Omega$. The difference in the amplitudes at the same position is due to different quantum scattering times [23–25].

In figure 2(a) the baseline corrected longitudinal resistance for S60 versus magnetic field strength is plotted for three different minimal gate voltages during a sweep cycle. For all traces, the gate voltage was swept from the maximal positive gate voltage of $V_{\text{max}} = +4.5$ V to the minimal gate voltages $V_{\text{min}} = -4.0$ V, $-4.5$ V, and $-5.0$ V. Afterwards the gate voltage was increased again and set constant at different $R_{xx}$-values for each $V_{\text{min}}$ corresponding to a fixed charge carrier density. Then the Hall traces were recorded. Note that the gate voltage during the measurement may be different but the charge carrier densities remain constant with $n \approx 6 \times 10^{11} \, \text{cm}^{-2}$. One observes that the SdH-oscillations appear at magnetic fields below 1.25 T for $V_{\text{min}} = -4.5$ V and $-4.0$ V. In addition, the oscillation amplitude is largest for $V_{\text{min}} = -4.5$ V. For $V_{\text{min}} = -5.0$ V, SdH-oscillations appear only at larger magnetic field values, i.e. well above 1.25 T and their amplitude is lower compared to the $V_{\text{min}} = -4.5$ V and $-4.0$ V values. From the amplitude of the SdH-oscillations, we extract the quantum scattering time for $V_{\text{min}} = 4.5$ V as presented in figures 2(b) and (c). Panel (b) shows an example of the baseline corrected $R_{xx}$ over $1/B$ for $V_{\text{min}} = -4.5$ V with the envelope function plotted in orange dashed lines. The baseline corrected amplitude of the oscillations can then be described by $\Delta R_{xx} = 4\gamma_\text{th} \exp \left( -\frac{\omega_c}{\omega_i} \right)$ with $\omega_c = \frac{eB}{m_e}$ being the cyclotron frequency and $\gamma_\text{th} = \frac{2\pi e^2 k_B T}{\hbar m_e}$ being the thermal factor ($e$ = elementary charge, $m_e$ = effective mass for the electrons, $k_B =$ Boltzmann constant and $\hbar =$ reduced Planck constant [23]). From that, we extract the values $\Delta R_{xx}$ divided by $\gamma_\text{th}$ (black squares) for each amplitude and plot them on a semi log plot (Dingle plot) as presented in panel (c). From the slope of the linear fit $\tau_q$ is extracted [23].

3. Results and theoretical model

The measurement procedure as explained in figure 2 was then carried out for all four samples with changing minimal gate voltages $V_{\text{min}} = -3$ to $-10$ V in steps of 1 V (for S60 two additional measurements for $V_{\text{min}} = -4.5$ V and $-5.5$ V were added) to extract $\tau_q$. For clarification, more details on the measurement procedure can be found in the supplemental material [26]. Furthermore, the transport scattering time $\tau_t$ was also extracted for comparison: $\tau_t = \frac{m_e \mu}{e}$, with $\mu$ being the mobility of the electrons. The measurement range
Figure 1. (a) $R_{xx}$ as a function of the top-gate voltage $V_{TG}$ at $B = 3$ T for sample S60. The down- and up-sweep are color-coded in red and black, respectively. (b) SdH-oscillations for a normalized (to the CNP) top-gate voltage in the range of $V_{TG} - V_{CNP} = 3–8$ V. From the oscillations the baseline $R_{xx,\text{base}}$ is subtracted for comparison. Evidently, the observed amplitudes of the SdH oscillations for the up-sweep, $R_{xx,\text{up}}$, are more pronounced compared to the down-sweep, $R_{xx,\text{down}}$, direction.

Figure 2. (a) $R_{xx}$ (baseline corrected) vs. the magnetic field at $V_{\text{min}} = -4$, $-4.5$, and $-5$ V for sample S60. For $V_{\text{min}} = -4.5$ V the oscillations appear at the lowest magnetic field values. For $V_{\text{min}} = -5.0$ V, the onset of SdH-oscillations occurs at the largest magnetic field value. (b) $R_{xx}$ (also baseline corrected) vs. $1/|B|$ for $V_{\text{min}} = -4.5$ V. The envelope function is plotted in orange dashed lines. This is used to extract the values $\Delta R_{xx}$ for each amplitude. In (c) the $\Delta R_{xx}$ values divided by a thermal factor $\gamma_{\text{th}}$. (black squares) are shown. From the slope of the linear fit $\tau_q$ is extracted.

It was used that the Fermi energy passes through the CNP and hence the gate training via $V_{\text{min}}$ can affect the potential in the gap region and the operation condition where topological edge states appear [19]. For $V_{\text{min}} \geq -3$ V we do not see a resistance peak in the up-sweep for most samples. Every measurement was performed at a fixed starting point regarding the charge carrier density with $n \approx 6 \times 10^{11}$ cm$^{-2}$. This allows us to compare each measurement from each sample. All four samples show a similar trend for $\tau_q$ in
can be reduced, and therefore the transport properties in general by electrical means instead of M Meyer (in (a)), the quantum scattering time is nearly constant and (when is not related to defect states at the surface but related to defects in the surrounding V to the starting position without gate training) as dashed lines for each sample min < max min − 21 (in (c)), as a function of the charge carrier density from ≈ min − min, start min is also dependent on the charge carrier density [ℏ until a minimal value can be seen for each sample = max − min = directly to the starting position τ min 28 min 0.11–0.12 ps. For clarity, we added the initial = min cm − − [up to 50%. The change of = max − min, start is nearly unaffected by the effects of the gate training. The initial τ q (when sweeping from V max directly to the starting position without gate training) is also added for each sample as a dashed line.

Figure 3. Quantum and transport scattering time as a function of the gate sweeping length V min = −3 to −10 V for the four different samples. All samples show a similar trend: Starting from V min = −3 V the quantum scattering time increases with larger gate sweeping lengths. A maximum is observable around V min = −4 to −5 V with τ q,max ≈ 0.12 ps (for S60 τ q,max ≈ 0.11 ps). Afterwards, τ q decreases until a minimum value for each sample and then starts to increase again. τ t is nearly constant and therefore unaffected by the effects of the gate training. The initial τ q (when sweeping from V max to the starting position without gate training) is also added for each sample as a dashed line.

dependence on V min. Starting at V min = −3 V, τ q is increasing with decreasing V min. For all samples, τ q peaks between V min = −4 and −5 V with τ q = 0.11–0.12 ps. For clarity, we added the initial τ q (when sweeping directly from V max to the starting position without gate training) as dashed lines for each sample and a detailed comparison with and without gate training can be found in figure S4 in the supplemental material [26]. Further reducing V min leads to decreasing τ q until a minimal value can be seen for each sample at a certain V min. As provided in the supplemental material [26], the decrease of τ q below V min < −5 V correlates with the appearance of the hysteresis. The hysteresis is typically assigned to charge trapping at the semiconductor/oxide interface [19, 21]. For V min ≥ −5 V and when τ q is increasing, no hysteresis is observable (see also figure S2 from the supplemental material [26]). Therefore, we assume that the improvement of τ q is not related to defect states at the surface but related to defects in the surrounding barrier material. As we show later, we can estimate the defect density and their spacing to the two-dimensional electron gas. We assume that the improvement of τ q is based on the reduction of charged defects that are close to the Fermi energy in the surrounding barrier material [27, 28]. While we can observe a prominent improvement of the quantum scattering time, the transport scattering time in comparison remains rather constant by variations of V min (squares in figure 3). Therefore, τ t is nearly unaffected by the gate training excluding thus a simple screening of impurities. However, τ t is less affected because of the (1-cos q) factor that weakens the part played by the forward (small angle) scattering in 1/τ t [29]. The dependencies of both scattering times on the gate training imply that the healed defects should be further away from the TQW. For all samples we observe a significant improvement of τ q up to 50%. The change of τ q shows that indeed via gate voltage training the quantum level broadening Γ = ℏ/2τ q can be reduced, which is consistent with a flattening of the potential landscape [19]. Thus by using the gate-training method, one can improve τ q and therefore the transport properties in general by electrical means instead of e.g. lowering the temperature [30]. In return, this indicates that with gate training higher operation temperatures are achievable.

Besides the dependency on V min, τ q is also dependent on the charge carrier density [31]. Figure 4 displays the transport scattering time τ t (in (a)), the quantum scattering time τ q (in (b)), and the ratio of both time scales, τ t/τ q (in (c)), as a function of the charge carrier density from 4 × 10¹¹ cm⁻²–14 × 10¹¹ cm⁻². The measurement was performed similarly to the previous ones with the gate voltage sweep starting at V max = 10 V, sweeping it to a fixed minimal gate voltage V min = −10 V, and then back to the measurement voltage V xx,start. This voltage V xx,start was changed between the measurements, which corresponds to different charge carrier densities.
The transport scattering time $\tau_t$ increases from 0.7 ps up to 3.5 ps and the quantum scattering time $\tau_q$ increases from 0.07 ps up to 0.12 ps. A power law dependence $n^b$ for both scattering times can be seen and the fitting enables us to extract powers of $b = 1.49$ and 0.42, for the transport and quantum scattering time, respectively. Therefore, the experimental ratio $\tau_t/\tau_q$ increases almost linearly with $b = 1.07$. In our trilayer well system, the positions (in either InAs- or GaSb-layers or in AlAsSb-barriers) and natures (acceptors, donors) of the dopants are unknown. Therefore, it is impossible to make an accurate modeling of the quantum and transport scattering times versus the 2D charge concentration $n$. The experiments (see figure 4) show that the latter is much longer than the former, which eliminates the possibility that the dominant static scatterers are short range. Most likely, they are charged impurities or traps. In addition, plotting their ratio against $n$ shows an almost linear behavior over a large range of $n$ values. We build a simplified model giving explicit predictions of the $n$ variations of the relaxation times and their ratio \cite{32}. The assumptions are that all the ionized impurities stay on a plane located at $|z_0|$ far from the planar 2D gas located on the plane $z = 0$. The screening is treated at the Thomas Fermi approximation and $T = 0$ K. Then, we get for $\tau_q$ and $\tau_t$:

\[
\frac{\hbar}{\tau_q} = \frac{m_e N_d}{\pi \hbar^2} \left( \frac{2\pi e^2}{\kappa} \right)^2 \int_0^\pi d\theta \frac{1}{(q_0 + 2k_F \sin \frac{\theta}{2})} \exp \left( -4k_F |z_0| \sin \frac{\theta}{2} \right) \tag{1a}
\]

\[
\frac{\hbar}{\tau_t} = \frac{m_e N_d}{\pi \hbar^2} \left( \frac{2\pi e^2}{\kappa} \right)^2 \int_0^\pi d\theta \frac{(1 - \cos \theta)}{(q_0 + 2k_F \sin \frac{\theta}{2})} \exp \left( -4k_F |z_0| \sin \frac{\theta}{2} \right) \tag{1b}
\]
where \( \kappa = 4\pi \varepsilon_0 \varepsilon_r \), with \( \varepsilon_0, \varepsilon_r \) being the vacuum and relative dielectric constants, respectively. \( k_F \) is the Fermi wavevector, \( q_0 = 2/\alpha_0 \) where \( \alpha_0 \) is the effective Bohr radius and \( N_d \) the 2D impurity concentration. \( \theta \) is the angle between the incident and scattered wavevectors. The two angular integrals \( I_q \) and \( I_r \) can be transformed to get:

\[
I_q = \frac{1}{2k_F |z_0|q_0^2} \int_0^{4k_F |z_0|} dt \frac{e^{-t}}{(1 + \frac{t}{2|z_0|q_0})^2} \sqrt{\frac{1}{1 - \left(\frac{t}{4k_F |z_0|}\right)^2}} \tag{2a}
\]

\[
I_r = \frac{1}{2k_F |z_0|q_0^2} \int_0^{4k_F |z_0|} dt \frac{e^{-t}}{(1 + \frac{t}{2|z_0|q_0})^2} \frac{1}{\sqrt{1 - \left(\frac{t}{4k_F |z_0|}\right)^2}} \tag{2b}
\]

Now the model is completed by assuming both \( 4k_F |z_0| \) and \( 2q_0 |z_0| \) are very large (much larger than 1). Then \( I_q \approx \frac{1}{2k_F |z_0|q_0^2} \) and \( I_r \approx \frac{1}{4k_F |z_0|q_0^2} \), thus \( \tau_q \approx 4k_F^2 |z_0|^2 \). Therefore, the model predicts that \( \tau_q \) scales as \( n^{1/2} \) and \( \tau_r \) scales as \( n^{3/2} \). Their ratio is thus linearly dependent on \( n \). These predictions qualitatively agree with our experiments. From the model, we can also extract the defect densities \( N_d \approx 3 \times 10^{11} \text{ cm}^{-2} \) and the average scattering plane distance of these defect states \( z_0 \approx 9 \text{ nm} \). However, while \( 4k_F |z_0| \approx 8.6 \) and thus much larger than 1, \( 2q_0 |z_0| \approx 1 \). Considering the actual values of the numerical integrals, one reappraises \( z_0 \approx 5 \text{ nm} \) and \( N_d \approx 1 \times 10^{11} \text{ cm}^{-2} \). Again, this points towards charged defects in the surrounding barrier material close to our TQW as the most prominent origin of scattering.

4. Conclusion

In summary, we evaluated the evolution of the quantum scattering time \( \tau_q \) in InAs/GaSb/InAs TQWs by gate voltage training. By sweeping the top-gate voltage from a maximum value \( V_{\text{max}} \) to a minimum value \( V_{\text{min}} \), we observe a hysteresis in the longitudinal resistance. Sweeps performed at low magnetic fields provide a voltage training. By sweeping the top-gate voltage from a maximum value \( V_{\text{max}} \) to a minimum value \( V_{\text{min}} \), we investigate this with another experiment in which we change the gate sweeping direction and observe an increase in the quantum scattering time of about 50% that corresponds to a decrease of the quantum level broadening whereas the transport scattering time is rather unaffected. Furthermore, the ratio of \( \tau_q \) and the transport scattering time \( \tau_r \) shows that long range Coulombic scattering is the dominant scattering mechanism and that defects in the barriers close to the TQW are the most prominent origin of scattering.

Data availability statement

The data cannot be made publicly available upon publication because they are owned by a third party and the terms of use prevent public distribution. The data that support the findings of this study are available upon reasonable request from the authors.

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