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Supplementary Materials: Gate-defined quantum point contacts in a germanium quantum well

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I. MEASUREMENT SETUP AND BASIC CHARACTERIZATION

In this section, we describe the measurement setups used in this work and the basic characteristics of the device.

Figure S1 illustrates the measurement setup used for the Hall bar structure. Contact leads are colored in blue and five of them are used in the measurements. An ac voltage $V_{\mathrm{ac}} = 500\,\mathrm{mV}$ is applied onto a 10 MΩ resistor via a lock-in instrument before connecting to the source lead, which would lead to a $\sim 50\,\mathrm{nA}$ ac current. In the mean time, ac current I_{ac} is measured from the drain lead in order to detect the actual current running in the circuit. Longitudinal voltage V_{xx} and transversal Hall voltage V_{xy} are measured with lock-in instruments. All lock-in instruments are operated at a frequency of 17.77 Hz. Three pairs of constrictions gates (orange) are applied with a voltage $V_{\mathrm{cg}} = -2.5\,\mathrm{V}$ to open up the regions below the constriction gates. As a global gate, the accumulation gate (light blue) with voltage V_{ag} is used to tune the carrier density in the whole device. A perpendicular magnetic field $B_{\perp}$ is applied during the Hall measurements. Then, we obtain carrier density p and hole mobility μ_{h} of the Ge quantum well as a function of the accumulation gate V_{ag} (see Figure S3). At $V_{\mathrm{ag}} = -10\,\mathrm{V}$, the carrier density p is $2.3 \times 10^{11}\mathrm{cm}^{-2}$ and the hole mobility μ_h is $3.5 \times 10^{5}\mathrm{cm}^{2}/(\mathrm{V\ s})$. In all the QPC measurements reported in the present work, V_{ag} is fixed at $-10\,\mathrm{V}$.

Figure S2 displays the measurement setup for QPC measurements. An ac voltage V_{ac} and a dc voltage V_{dc} are summed up with a summing module before feeding into the source lead. An ac current I_{ac} is measured with the help of a current pre-amplifier. Three QPCs are defined with three pairs of constriction gates with voltage V_{cg1}, V_{cg2} and V_{cg3}. The accumulation gate voltage V_{ag} tunes the carrier density in the device globally. In QPC measurements, magnetic field is applied perpendicularly as well.

II. SERIAL RESISTANCE SUBTRACTION

As seen in Figure S2, QPCs are measured in a so-called two-terminal setup, where measurement circuit connect to the source (S) and drain (D) leads of the device. In this case, the measured resistance of the device is composed of three parts (1) contact resistance in the S/D leads, (2) resistance of the Ge quantum well between a dedicated QPC and two contacts, (3) resistance of a dedicated QPC. Normally, we believe contact resistance is constant even varying measurement conditions. However, the second part of the resistance is modulated with external magnetic field, especially in large magnetic fields. Therefore, the serial resistance R_{s} (first two parts) need to be subtracted and the value should be adjusted depending on external magnetic field.

In the presence of R_{s}, both differential conductance G_{diff} and dc bias voltage V_{b} need to be re-calculated. The differential conductance is calculated as $G_{\mathrm{diff}} = 1/(V_{\mathrm{ac}}/I_{\mathrm{ac}} - R_{\mathrm{s}})$. In order to correct dc voltage bias, dc current through the device is required. Initially, we found that ac signal has a noticeable influence on dc current measurement. We therefore acquire the dc current by integrating ac signals at varied V_{dc} with the formula $I_{\mathrm{dc}}(V_{\mathrm{x}}) = \int_0^{V_{\mathrm{x}}} \frac{I_{\mathrm{ac}}}{V_{\mathrm{ac}}}\, dV_{\mathrm{dc}}$. After having I_{dc}, we correct voltage bias as $V_{\mathrm{b}} = V_{\mathrm{dc}} - I_{\mathrm{dc}} \cdot R_{\mathrm{s}}$.

Serial resistance R_{s} is chosen such that the first conductance plateau is $2e^2/h$ after subtraction. Considering the influence of magnetic field, R_{s} is obtained and subtracted in such a way at each magnetic field.

III. ADDITIONAL DATA

In this section, we provide additional figures where essential parameters displayed in the main article are extracted.

Figure S4 shows bias-spectroscopy measurements of QPC2 and QPC3 in the absence of magnetic field. From the figure, we obtain quantization energies of the 1D subbands for the

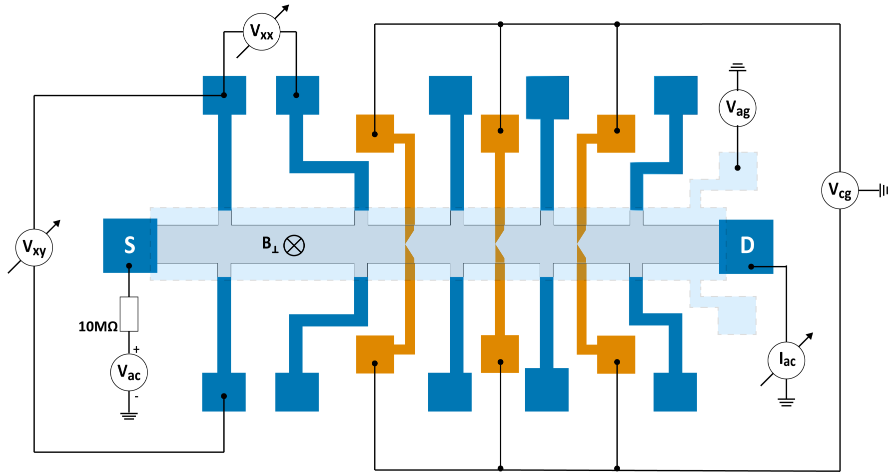

FIG. S1. Measurement setup for the Hall bar structure. An ac voltage $V_{ac} = 500\,\mathrm{mV}$ is applied with a lock-in instrument to the source lead (S) and ac current I_{ac} is measured from the drain lead (D). A 10 MΩ resistor is used to maintain an ac current of $\sim 50\,\mathrm{nA}$. Longitudinal voltage V_{xx} and transversal Hall voltage V_{xy} are measured with lock-in instruments. All lock-in instruments are operated at a frequency of 17.77 Hz. Contacts are colored in blue and five of them are used in the measurements while rest contacts are floated. The voltages of three pairs of constriction gates (orange color) are fixed at $V_{cg} = -2.5\,\mathrm{V}$ to open up the channel below the constriction gates. As a global gate, the accumulation gate (light blue) with voltage V_{ag} is used to tune the carrier density in the whole device. A perpendicular magnetic field $B_{\perp}$ is employed during the Hall bar measurements.

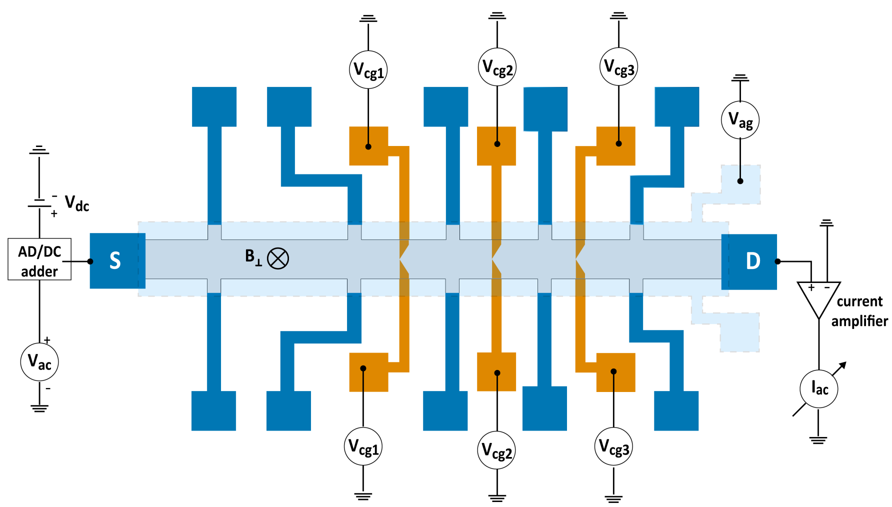

FIG. S2. Measurement setup for QPC measurements. An ac voltage V_{ac} and a dc voltage V_{dc} are summed up with a summing module before feeding into the source lead, while the ac current I_{ac} is measured with the help of a current pre-amplifier. Three QPCs are defined with three pairs of constriction gates with voltage V_{cg1}, V_{cg2} and V_{cg3}. The accumulation gate with voltage V_{ag} is used to tune the carrier density in the device globally.

two QPCs. Corresponding results are shown in Figure 2(d) in the main article.

Figures S5-S7 are bias-spectroscopy measurements of the three QPCs in perpendicular magnetic fields $B_{\perp}$. From these measurements, we obtain Zeeman energies of 1D subbands in QPCs at different $B_{\perp}$ and corresponding data are present in Figures 3(e)-3(g) in the main article.

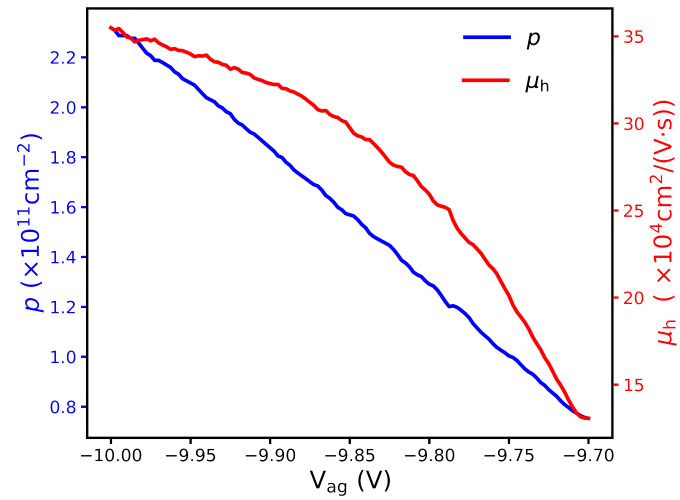

FIG. S3. Carrier density p and hole mobility μ_h in the Ge quantum well as a function of the accumulation gate V_{ag}. Corresponding data are measured from the Hall bar structure with a measurement setup shown in Figure S1. The accumulation gate is fixed at $V_{ag} = -10\,V$ in all the QPC measurements.

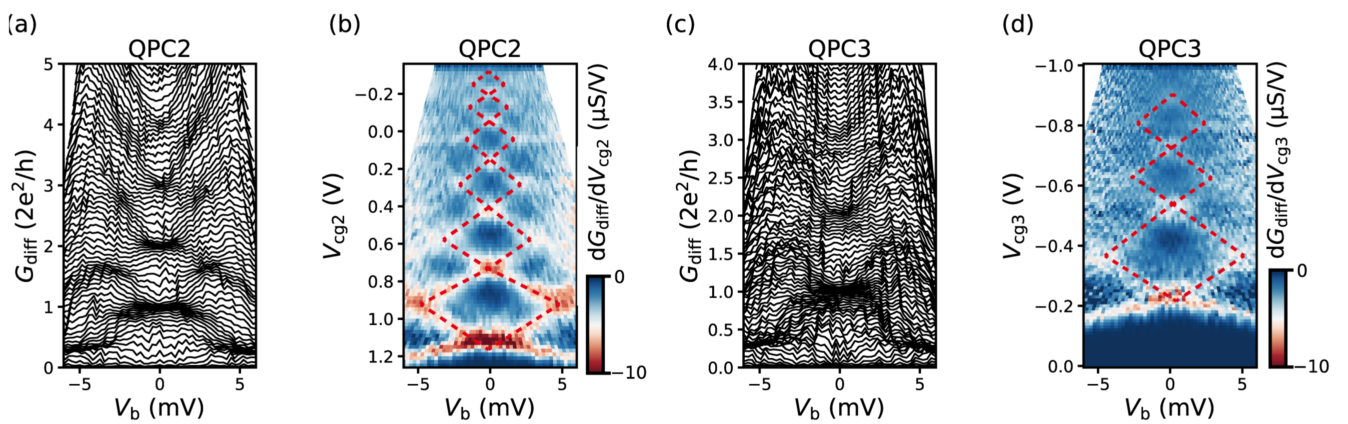

FIG. S4. (a), (b) Waterfall plot and transconductance graph of QPC2 at $V_{cg1} = V_{cg3} = -2.5\,V$ and $B = 0$. (c), (d) Waterfall plot and transconductance graph of QPC3 at $V_{cg1} = V_{cg2} = -2.5\,V$ and $B = 0$. Red dashed lines in transconductance graphs denote the boundaries of the diamonds, where quantization energies between successive 1D subbands are obtained. With Eq.(1) in the main text, the effective length L_n of the first six subbands of QPC2 is estimated to be 12, 29, 42, 52, 65 and 80 nm, respectively. L_n of the first three subbands of QPC3 is estimated to be 12, 29 and 42 nm, respectively.

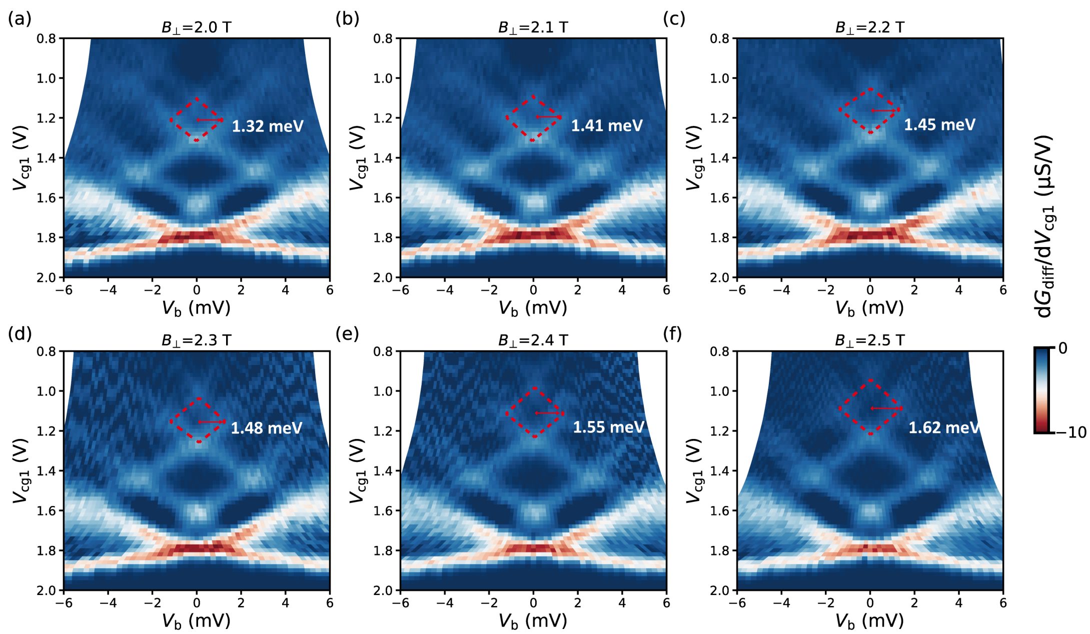

FIG. S5. Bias-spectroscopy measurements of QPC1 at different perpendicular magnetic fields $B_\perp$. Red dashed lines denote the diamond formed by the second subband with finite Zeeman energies. The extracted Zeeman energies of the second subband at different $B_\perp$ are displayed in Figure 3(e) of the main article.

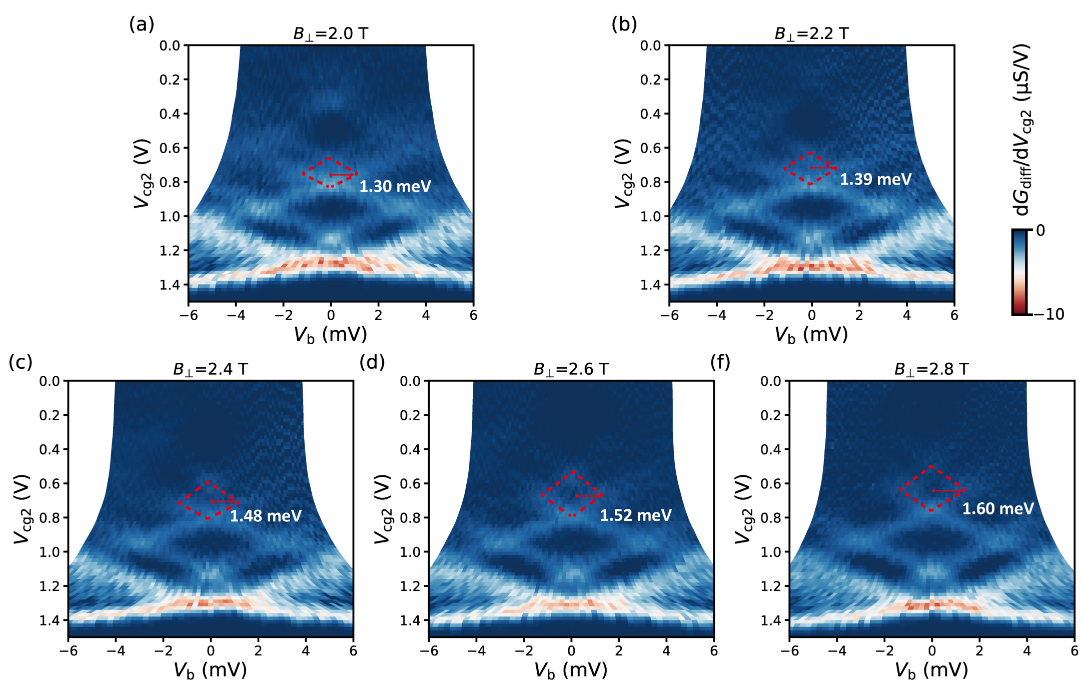

FIG. S6. Bias-spectroscopy measurements of QPC2 at different $B_\perp$. Red dashed lines denote the diamond formed by the second subband with finite Zeeman energies. The extracted Zeeman energies of the second subband at different $B_\perp$ are displayed in Figure 3(f) of the main article.

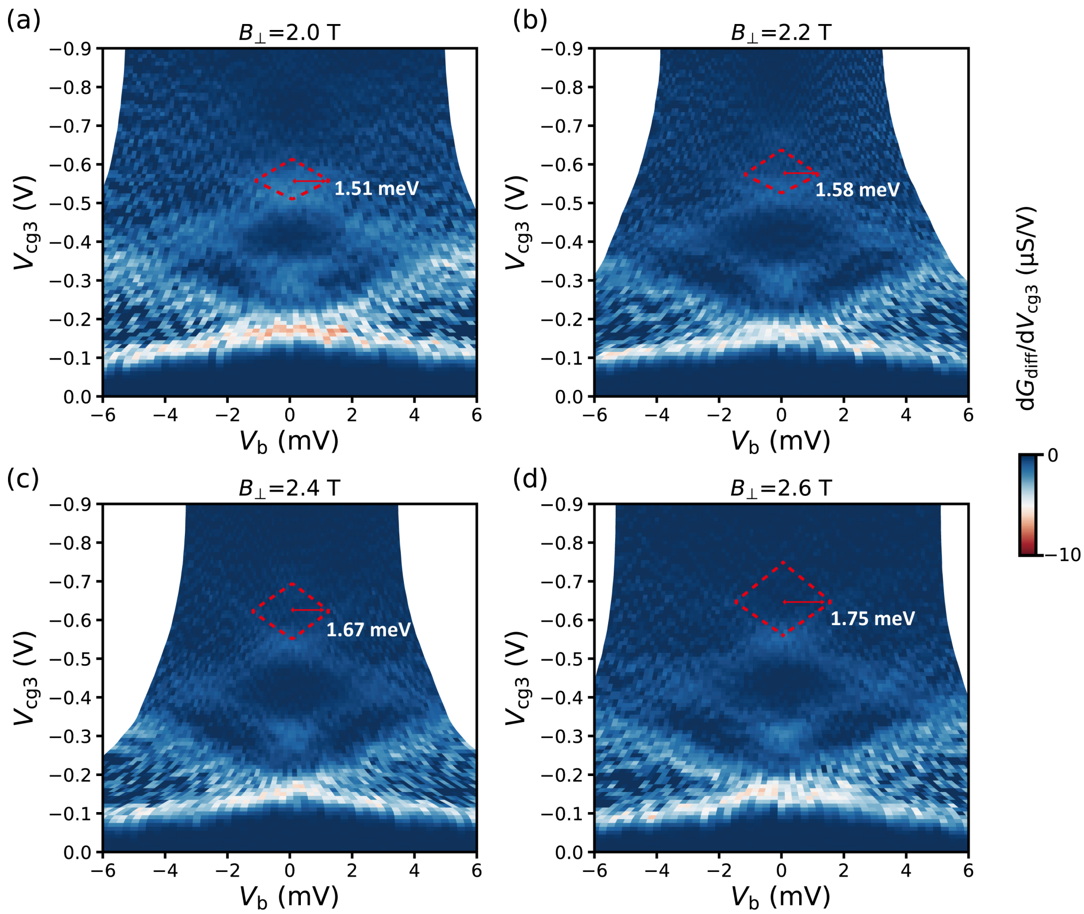

FIG. S7. Bias-spectroscopy measurements of QPC3 at different $B_\perp$. Red dashed lines denote the diamond formed by the second subband with finite Zeeman energies. The extracted Zeeman energies of the second subband at different $B_\perp$ are displayed in Figure 3(g) of the main article.