Spin qubits implemented in semiconductor quantum dots (QDs) are attractive candidates for enabling solid state quantum computing [1][8]. In particular, singlet-triplet spin qubits, where the logical qubits are encoded in a two-electron spin system in double quantum dots (DQDs) turned out to be very interesting as they allow fast quantum gate operations avoiding fast microwave pulses [1][8]. For such qubit systems control over the interdot tunnel coupling and hence the exchange interaction between the electrons in the two coupled QDs is essential [8][11]. Typical tunnel coupling energies are on the order of 1 GHz for silicon [7] and up to 3 GHz for GaAs-based [6] spin qubits allowing fast quantum gate operations.

Bilayer graphene (BLG) is an attractive host material for spin qubits due to its small spin-orbit and hyperfine interaction, as well as the possibility to open a gate voltage controllable band gap [12][13]. The development of ultra-clean van der Waals heterostructures where a BLG sheet is encapsulated in hexagonal boron nitride (hBN) [15] and a graphite crystal is used as a back gate [16] has lead to a boost in device quality and has enabled the implementation of well-defined QDs [17][20] and DQDs [21][22]. Typically, in such BLG DQD systems just one gate is used per QD and the interdot tunnel barrier is tuned by stray fields of these gates [22]. Hence, the architecture commonly used in BLG DQDs inhibits the control of the tunneling barriers independent of the charge occupation of the QDs. The implementation of separate sets of gates, one controlling the dot occupation and one controlling the tunnel coupling, is a well-established technique in different types of GaAs-based QD devices [23][26]. In electron and hole QD systems based on SIMOS, Si/SiGe and Ge/SiGe heterostructures, an additional gate layer implementing interdigitated finger gates has been used for that purpose [27][31].

Here, we show independent gate control of the tunnel coupling and the mutual capacitive coupling in a bilayer graphene double quantum dot device while keeping the dot occupations and the dot size, i.e. the charging energy, constant. In short, we demonstrate the operation of an advanced device architecture with interdigitated gate fingers that allows for a precise modulation of the band edge profile defining the confinement potential and tunneling rates.

Fig. 1(a) shows a scanning electron micrograph of a fabricated device. It consists of a BLG flake, which has been encapsulated between two crystals of hexagonal boron nitride of approximately 25 nm thickness using conventional dry van-der-Waals stacking techniques [15][32]. The heterostructure is placed on a graphite flake, acting as a back gate [21]. On top of this stack, Cr/Au split gates with a lateral separation of 130 nm are deposited. Separated from the split gates by a 25 nm thick layer of atomic layer deposited (ALD) Al₂O₃, we fabricated 90 nm wide finger gates (FGs) with a pitch of 150 nm. To avoid ungated regions along the channel, we fabricate a second layer of FGs, with same width and pitch, separated from the first one by an additional layer of Al₂O₃. A schematic cross section through the heterostructure and the gate stack is shown in Fig. 1(b) where the positions of the left (L) and right (R) QD are highlighted. Fig. 1(c) shows a simplified circuit diagram of a DQD. All measurements are performed in a ⁴He/⁴He dilution refrigerator at a base temperature of 20 mK and an electron temperature of around 60 mK, using standard DC measurement techniques.

In order to form QDs in the extended BLG sheet, we first define a narrow conductive channel by opening a displacement field induced band gap underneath the split gates. For this, we apply a constant back gate voltage of $V_{BG} = -1.534 \, V$ and a split gate voltage of $V_{SG} = 1.7 \, V$ resulting in a band gap of around 30 meV in the regions below the SGs and an overall p-doped channel. Second, we make use of the individual FGs to locally tune the band edges of the gapped BLG with respect to the Fermi level. For example, when applying a positive voltage on...
both finger gates GL and GR – while keeping all other FGs at 0 V – we tune the band edges such that tunneling barriers form below GL and GR allowing to fully suppress transport through the channel. This is verified by the conductance trace shown in Fig. 1(d) (see black arrow). For smaller finger gate voltages, we observe regular Coulomb resonances, which we attribute to a hole QD (hQD) below CG, as for large gate voltages we enter the regime of an electron DQD (eDQD).

The different transport regimes become more apparent when investigating the conductance as a function of \( V_{GL} \) and \( V_{GR} \) (see Fig. 1(e)); the dashed arrows mark the cross-section shown in Fig. 1(d). In this charge stability diagram, we highlight the different transport regimes (see labels I, II, III and IV; corresponding schematics of the band edge diagrams are shown in Fig. 1(f)).

At low voltages around \( V_{GL} \approx 3.8 \text{V} \) and \( V_{GR} \approx 4 \text{V} \) (regime I), we observe hyperbolically shaped charge addition lines indicating the presence of a single hole QD (see dashed line in Fig. 1(e)). Increasing both gate voltages, the hole QD is depleted more and more due to the capacitive cross-talk of these gates to the QD and we observe the transition to an electron DQD (regime II). The DQD regime shows the characteristic hexagonal pattern of the charge addition lines and extends over a wide voltage range before the increasing tunnel coupling leads to the transition to a single QD. Interestingly, in an intermediate region, an ambipolar triple QD is formed, where the outer two QDs are occupied by one electron and the inner QD by a single hole.

Furthermore, we can manipulate the band edges to form different ambipolar DQD configurations. In regime III \((V_{GL} \approx 3.6 \text{V} \text{ and } V_{GR} \approx 4.5 \text{V})\), a hole-electron ambipolar DQD is formed where the horizontal lines indicate charge transitions of the electron QD while the curved lines show transitions of the hole QD. A further reduction of \( V_{GL} \) at constant \( V_{GR} \) lifts the tunnel barrier separating the hole QD from the left reservoir leaving only a
single electron QD below the right gate (regime IV). The opposite charge configuration can be observed in the bottom right of the shown charge stability diagram. This measurement proves the versatility of the device which allows smooth transitions between unipolar and ambipolar QD configurations. Consistent results have also been obtained from QD configurations formed by other pairs of finger gates.

In the following, we focus on the interdot coupling of the electron DQD (regime II). In order to study the influence of the central gate (CG) located in the second finger gate layer between the gates GL and GR, we measure charge stability diagrams for different \( V_{CG} \) values with \( \Delta V_{G} \) and \( V_{det} \) as a function of \( E_{det} \) (see Fig. 2(a)-(c)). Two significant effects can be observed: First, all DQD and hole dot transitions in the charge stability diagram are shifted towards lower \( V_{GL} \) and \( V_{GR} \) values with increasing \( V_{CG} \) due to cross capacitances of the CG and the two QDs. Second, the interdot tunnel coupling in the DQD regime increases as the conduction band edge is pushed more and more towards the Fermi level. This effect is illustrated in the schematics shown in Fig. 2(d). At high \( V_{CG} \) (and high \( V_{GL} \) and \( V_{GR} \)), the tunneling barrier is lifted fully, eventually leading to the formation of a large single QD which manifests in the appearance of diagonal charge addition lines (see e.g. dashed lines in Fig. 2(e)-(g)). Fig. 2(e)-(g) show close-ups of the few electron DQD regime (around the occupation of \((4,3)\) electrons; see dashed rectangles in Fig. 2(a)-(c)). Qualitatively, the effect of increasing interdot tunnel coupling becomes apparent by the broadening of features within the triple points, as well as by the significantly enhanced conductivity along the co-tunneling lines.

For a quantitative analysis of the impact of the central gate on the interdot coupling and the QD size, we determine the mutual capacitive coupling energy \( E_{m} \), the interdot tunnel coupling \( t_{m} \), and the charging energies \( E_{C}^{R,L} \) as a function of \( V_{CG} \). Fig. 3(a) shows the charge stability diagram of an individual pair of triple points highlighting the relevant quantities to extract \( E_{m} \) and \( t_{m} \). We determine the charging energy of each of the QDs from the charge stability diagrams as shown in Figs. 2(e)-(g) according to \( E_{C}^{R,L} = \alpha^{R,L} V_{GL,GR} \) with the lever arms \( \alpha^{R,L} = V_{SD}/\delta V_{GL,GR} \). The mutual capacitive coupling energy is given by \( E_{m} = \alpha^{R} \delta V_{GL} \). The interdot tunnel coupling \( t_{m} \) can be extracted from current traces recorded along the detuning energy \( (E_{det}) \)
axis (see e.g. black arrow in Fig. 3(a)). A representative measurement is shown in Fig. 3(b), where the detuning axis corresponds to a cut through the triple point shown in Fig. 3(a). Resonances inside the triple point are clearly visible, which correspond to transport involving excited states. We fit the current through the ground state according to a model assuming a Lorentzian line shape [34-37] resulting in the limit of $t_m \ll \Gamma_{L,R}$ to

$$I(E_{\text{det}}) = \frac{4e^2t_m^2/\Gamma_R}{1 + (2E_{\text{det}}/\hbar\Gamma_R)^2},$$

where $\Gamma_{L,R}$ are the tunnel rates to the left and right lead, respectively.

The results of the detailed analysis are summarized in Fig. 4. Fig. 4(a) shows that the mutual capacitive coupling $E^m$ increases monotonically with $V_{CG}$, which can be explained by the fact that the two electron QDs (L and R) are pushed closer to each other for increasing $V_{CG}$ (see sequence shown in Fig. 2(d)). This results in an increase of $C_m$ and thus to an increase of $E^m$. Consistently, for lower dot occupations this effect is slightly less pronounced resulting in a lower increase. The observed monotonic behaviour is in contrast to earlier work on a physically etched single-layer graphene DQD [33] and on a gate-defined DQD in an etched graphene nanoribbon [35], which showed a non-monotonic dependency of $E^m$ on the gate voltage. Furthermore, in etched BLG DQDs, $E^m$ increased or decreased with the gate voltage depending on the charge occupation of the DQD [33, 34].

Fig. 4(b) shows that $V_{CG}$ has rather little effect on the charging energy and hence the size of the QDs. From a simplified plate capacitor model approximating the QDs as discs separated from the back gate by 25 nm of hBN, we determine upper limits for the effective QD diameters $d_L = 220$ nm and $d_R = 270$ nm in the few electron regime and $d_L = 174$ nm and $d_R = 184$ nm in the low electron regime. These estimates are in reasonable agreement with the lithographic dimensions. The pitch of the plunger gates measures 150 nm and the split gates are separated by around 130 nm.

Finally, in Fig. 4(c), we show the tunnel coupling $t_m$ for a fixed charge carrier occupation for different gate voltages $V_{CG}$. We show that $t_m$ can be tuned monotonously in the range from 1 to 4 GHz at the (4,2)-(3,3) transition and from 0.7 to 2.5 GHz at the (2,0)-(1,1) transition covering the operating regime for silicon and GaAs spin qubit devices [6, 7].

In conclusion, we studied a BLG QD system where we introduced a second layer of finger gates forming a dense pattern of gates. We focus on an electron DQD where two dedicated finger gates act as plunger gates controlling the number of charge carriers on each of the QDs from the few-electron regime down to the very last electron. An additional gate, positioned in between those, controls the interdot coupling. Tuning the interdot tunnel coupling in the range of 1 to 4 GHz at a constant charge occupation meets a basic requirement making BLG QD arrays suitable building block for spin qubit devices, which brings BLG closer as a serious quantum technology platform.

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