

Coupling effects between widely separated layers of self-assembled quantum dots

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Coupling effects between self-assembled quantum dots in different layers separated by approximately 200 nm are studied by transient capacitance spectroscopy. This coupling manifests itself via interdependent time constants of the transients. Two different coupling mechanisms that act over such large spacings are identified. The first one is electrostatic coupling, caused by electrons in the first layer that modify the electric field at the site of the second layer and with it the lifetime of the discrete states in the quantum dots therein. The second mechanism is cascade coupling, where electrons emitted by the first layer are recaptured by the second layer. A rate equation model combined with self-consistent band structure calculations provides a quantification of the proposed mechanisms.

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I. INTRODUCTION

Self-assembled quantum dots (SAQDs) are quasi-zero-dimensional semiconductor islands embedded in a semiconductor host crystal with a significantly different band structure, leading to charge confinement in the quantum dots [1,2]. The energy spectra of such *artificial atoms* have been studied in great detail, both by optical as well as by electronic measurements, and the squared wave functions of the most relevant *s* and *p* states have been mapped out. Beyond fundamental research [3–8], SAQDs have also found their way into several applications [9], in particular in single photon sources [10], light-emitting diodes [11], and, most prominently, as lasers in the telecom window [12,13]. Furthermore, their potential as memory cells [14–16] and memristors [17] has been elucidated.

In these studies, the coupling of SAQD states to their environment is a key point, comprising, for example, coupling to photons, strong coupling to cavities in Rabi oscillators, or coupling to a reservoir via elastic tunneling. Also, quantum couplings between different SAQDs have been studied. For distances below ≈ 10 nm, quantum mechanical coupling can lead to the formation of artificial molecules [18–25] with the potential to implement quantum computation concepts [26,27]. At somewhat larger distances between SAQDs in two layers separated by ≈ 20 nm, electrostatic coupling between the dots has been reported, which can be described by a Coulomb blockade term [28].

Here, we report the observation of interdot couplings between SAQDs in adjacent layers with a large spatial separation of ≈ 200 nm, such that both correlated growth across the layers [29,30] as well as electron tunneling between the dots [18–25] can be safely excluded. The coupling is detected via capacitance transients originating from capture and emission of electrons by the SAQDs. The transients can be attributed unambiguously to a specific SAQD layer due to their strong bias voltage dependence, with time constants modified by the couplings. Large SAQD layer distances are present in a variety of structures like light-emitting diodes [31,32], quantum dot lasers [33,34], or solar cells [35,36].

In Sec. II, the samples and the measurement concepts are described. Our results and their interpretation are presented in Sec. III, and we summarize our findings in Sec. IV.

II. EXPERIMENTAL DETAILS

The samples used in our study are depicted in Fig. 1. The relevant structure was grown on top of a GaAs single crystal substrate by molecular beam epitaxy. A 20-period GaAs/AlAs short-period superlattice (SPS) prevents diffusion of defects from the substrate into the critical structure and is followed by 50 nm undoped GaAs. A degenerately Si-doped (doping density $2 \times 10^{18} \text{ cm}^{-3}$) layer of GaAs acts as back electrode and electron reservoir. On top of this layer, a 938-nm GaAs layer with a nominal doping density of $n_D = 2 \times 10^{16} \text{ cm}^{-3}$ is grown. Herein, two layers of InAs SAQDs are embedded at distances of 232 nm and 436 nm below the sample surface, which we denote by *upper layer* *u* and *lower layer* *ℓ*, respectively. Each SAQD layer is surrounded by an undoped GaAs layer of 24 nm thickness. The SAQDs have a sheet number density of $n_{QD} = 10^{14} \text{ m}^{-2}$, which corresponds to approximately 9×10^6 quantum dots in each layer underneath the active area of $0.3 \text{ mm} \times 0.3 \text{ mm}$, defined by a layer of 7 nm Cr and 250 nm Au on the sample surface acting as a gate electrode. For comparison purposes, samples containing

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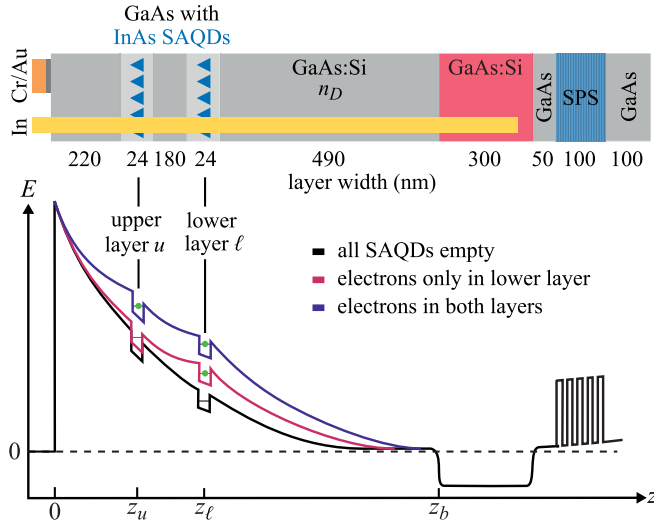


FIG. 1. Sketch of the sample layout (top, SPS denotes a short-period superlattice and n_D is the doping density) and schematic conduction band profile for various SAQD layer occupancies (bottom, the full green circles denote electrons). The dashed line denotes the Fermi level in the back contact.

only the upper (sample U, $z_{QD} = 230$ nm) or the lower layer (sample L, $z_{QD} = 410$ nm), respectively, were prepared.

The experimental setup used for the transient capacitance spectroscopy has been described in detail elsewhere [37]. In brief, an AC test voltage with an amplitude of 20 mV and a frequency between 12 and 15 MHz was created by a HF2LI lock-in amplifier (Zurich Instruments), superimposed to a DC bias voltage (Tektronix AFG31051) and applied to the top gate with respect to the back electrode, which was kept at virtual ground via a HF2TA transimpedance amplifier (Zurich Instruments) with $Z = 1$ k Ω . Its out-of-phase voltage, which is proportional to the capacitance, was recorded with a sampling rate of ≈ 115 kHz using the lock-in amplifier with a time constant set to 1 μ s of a first-order filter, allowing a temporal resolution of the capacitance $C(t)$ of $\Delta t < 9$ μ s. The sample was mounted into a liquid nitrogen cryostat, in which all measurements were taken at a temperature of 77 K.

We study the capacitance transients in response to DC voltage steps, composed of a preparation voltage V_p of 10 ms duration, followed by a measurement voltage V_m , also applied for 10 ms with a transition time of 100 ns in between. All combinations of V_m and V_p in the range $V \in [-3$ V, 0.4 V] are measured in steps of 40 mV. For each combination, the capacitance transient is recorded during V_m . The measurements are repeated 1000 times to obtain acceptable signal-to-noise ratios, and the averaged transients are analyzed. For an overview, we present characteristic measurements using the *lock-in DLTS* signal $S(V_p, V_m)$, defined as

$$S(V_p, V_m) = \frac{1}{P} \left(\int_0^{P/2} C(t) dt - \int_{P/2}^P C(t) dt \right), \quad (1)$$

where $P \leq 10$ ms is the rate window, i.e., the interval over which the transient is evaluated. S depends on P as well as on the time constants of the transients. [37] In comparison to other evaluation techniques, $S(V_p, V_m)$ can be measured in

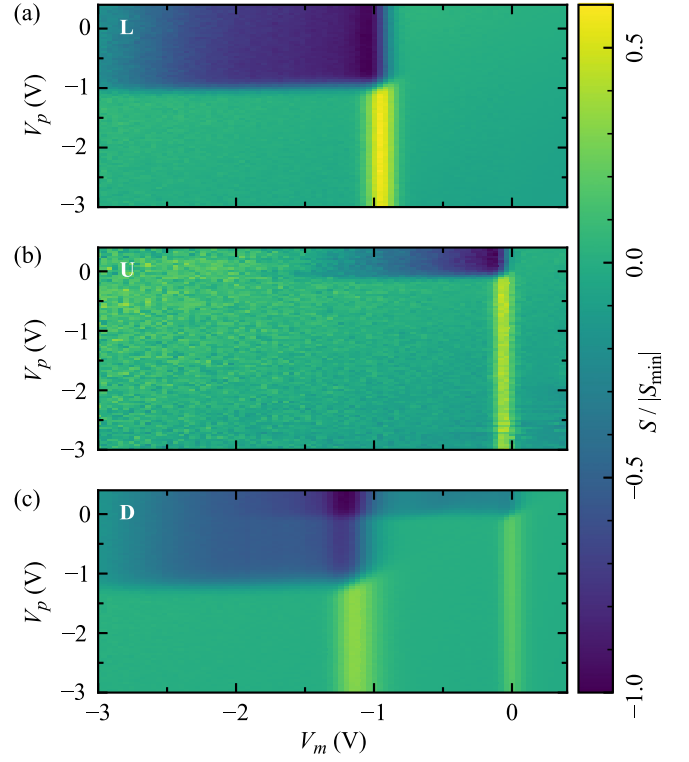


FIG. 2. Color plot of the normalized lock-in DLTS signal $S(V_p, V_m)$, where the normalization is performed with respect to the global minimum of the signal $S_{\min}$, at a temperature of 77 K and a rate window of $P = 500$ μ s starting at $t = 0$ after changing from V_p to V_m [see Eq. (1)], shown for the samples containing (a) only one layer at $\approx z_\ell$ (sample L), (b) one layer at z_u (sample U), and (c) the double layer (sample D).

a relatively short time at the expense of capacitive resolution and is therefore used for landscape measurements over large parameter ranges. We note that the data have been corrected for changes in S due to the sensitivity dC/dV , see the Supplemental Material for details [38].

III. RESULTS AND INTERPRETATION

In Fig. 2, normalized lock-in signal $S(V_p, V_m)$ as measured on the two single layer (L and U) and on the double layer (D) samples are shown. The lock-in DLTS signal of sample L has been discussed elsewhere in terms of the voltage-dependent capture and emission rates which determine the measured time constants [37]. In brief, negative S values indicate electron emission from the SAQDs, the time constant τ of which increases as V_m is increased. The asymmetric shape of the emission peak originates from a sharp increase of the capacitance amplitude and capture time constant as a function of decreasing V_m due to increasing emission amplitude, in combination with weakly decreasing emission time [37]. In sample L [Fig. 2(a)], for example, emission is only visible in the range $V_p \gtrsim -1$ V, since for lower preparation voltages the SAQDs remain empty. Rather, in this interval, a capture peak centered at $V_m = -0.96$ V is observed, seen as a yellow stripe in Fig. 2(a).

$S(V_p, V_m)$ of sample U, shown in Fig. 2(b), resembles that of L, displaced along both voltage axes due to the different location of the layer. Both peaks are sharper, reflecting the steeper dependence of the electric field on V_m as the Schottky interface is approached.

$S(V_p, V_m)$ of sample D shows two narrow peaks at $V_m = -1.16$ V for $V_p \lesssim -1.16$ V, and at $V_m = 0$ V for $V_p \lesssim 0$ V, see Fig. 2(c). They indicate capture of electrons in the lower and the upper layer, respectively, within the selected time window appearing in the half-plane $V_p < V_m$. For $V_m \lesssim -1$ V and $V_p \gtrsim -1.16$ V, a broad negative signal is visible, which can be attributed to emission from the lower layer. Likewise, the interval $V_m \lesssim 0$ V and $V_p \gtrsim 0$ V shows emission from the upper layer. To a coarse approximation, $S(V_p, V_m)$ of sample D resembles just a superposition of the signals from samples L and U. However, pronounced deviations are visible as well. First of all, the peak positions in D show a larger spacing along the V_m axis, with the capture peak of layer ℓ shifted to lower V_m (i.e., higher capture rates at the same bias voltage), and that one of layer u is displaced to higher V_m . Likewise, the spacing of the emission peaks has increased as compared to that of the individual layer samples, and the transitions from capture- to emission-dominated transients are displaced towards lower V_p for layer ℓ and towards higher V_p for layer u .

In the following, we interpret these deviations in terms of coupling between the SAQD layers via their influence on the time constants. By $V_p = +0.4$ V, the s states of the SAQDs in both layers in sample D are filled at $t = 0$, a scenario labeled as D_{lu} . Likewise, $V_p = -1$ V was applied to D in order to fill only the lower layer, a configuration denoted by D_ℓ . To fill the layers in samples U and L, V_p pulses of $+0.4$ V and -0.72 V strength were applied, respectively.

In Fig. 3(a), four typical capacitance transients as obtained for different V_m in the D_{lu} scenario are shown. All transients measured at sample D can be fitted to bi-exponential functions with a correlation coefficient > 0.992 , i.e.,

$$C(t) = C_\infty - \sum_{j \in \{+, -\}} C_{0,j} e^{-t/\tau_j}, \quad (2)$$

while $C_0 = \sum_j C_{0,j}$ denotes the amplitude of the signal and C_∞ the steady state capacitance. The two time constants $\tau_\pm$ are tentatively attributed to emission from the s_1 and s_2 states; the two lowest energy states of a single SAQD, which is strictly valid only for negligible capture [37,40] and requires some refinement below. Since the s_2 levels are shifted to larger energy by the Coulomb blockade, they have a shorter lifetime than the s_1 states. Furthermore, it should be noted that for a strong dependence of the capture time constant on the bias voltage, nonmonotonous transients have been reported [41], thus rendering Eq. (2) invalid. For the sample parameters in the present experiments, however, such behavior is negligible [38]. In Fig. 3(b), the functions $\tau_\pm(V_m)$ as measured on sample L, U, and on sample D in its two different configurations are compared. For L, U, and D_ℓ , they are readily understood in terms of previous work: the maximum of τ originates from the decreasing emission rate as V_m is increased, in combination with the onset of electron capture, also indicated by positive lock-in signal S in Fig. 3(b), close to the maximum of τ with a rate that increases rapidly with V_m [37,42]. The $\tau_\pm(V_m)$

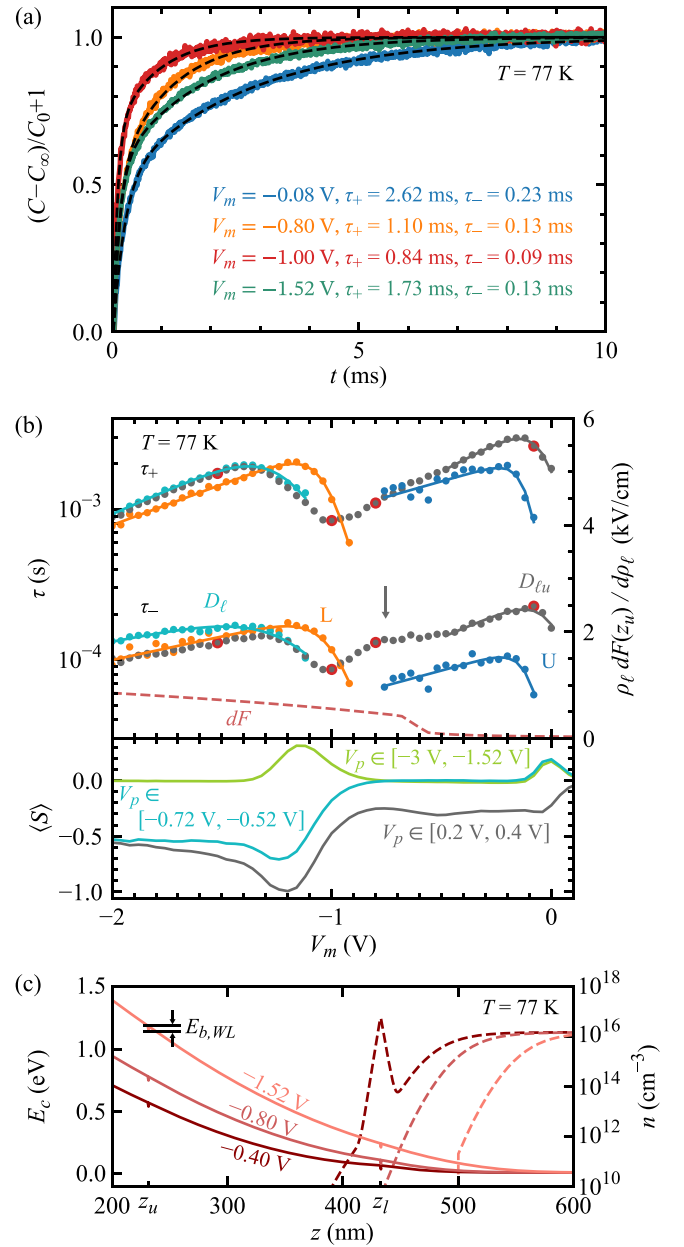


FIG. 3. (a) Typical capacitance transients for sample D at various V_m after preparation by $V_p = 0.4$ V with their biexponential fits (dashed lines) normalized by the fit parameters. (b) Top: time constants $\tau_+(V_m)$ and $\tau_-(V_m)$ (circles) as obtained for samples U, L, and D in the configurations D_ℓ and D_{lu} . The arrow denotes the kink discussed in the main text. The time constants obtained from the transients shown in (a) are marked in black. The full lines represent fits to the rate equation model. The calculated change $dF(V_m)$ of the electric field at upper layer position z_u originating from occupied SAQDs ($\rho_\ell = -2$ e/SAQD) in the lower layer is shown as a dashed red line (right axis). Bottom: Averaged lock-in signal $\langle S \rangle$ of sample D from data also shown in Fig. 2(c). (c) Conduction band profile (solid lines, left axis) and electron density (dashed lines, right axis) as calculated with a Poisson-Schrödinger solver for characteristic bias voltages. The indicated binding energy $E_{b,WL}$ of the WL state equals ≈ 30 meV [39].

functions for the D_{lu} configuration [dark gray circles in Fig. 3(b)], however, are nontrivial and contain the information of interest here.

First, we compare the two time constants measured at U to those found for D_{lu} . In the range $-0.8 \text{ V} \leq V_m \leq -0.6 \text{ V}$, τ_+ has very similar values. As V_m is increased further, however, τ_+ increases with a higher slope in D_{lu} than in U. This is readily explained by the presence of layer ℓ : self-consistent Poisson-Schrödinger calculations [43], see Fig. 3(c), reveal that by applying voltages $\gtrsim -0.6 \text{ V}$, the space charge layer ends between layers u and ℓ . In addition, not only the s states, but also the p and d states as well as the wetting layer (WL) of layer ℓ get occupied (see below). The WL will get occupied with increased voltage [44] and based on a typical ionization energy of $\approx 30 \text{ meV}$, it can be filled up to an electron density of $n_{WL} \approx 9 \times 10^{11} \text{ cm}^{-2}$ corresponding to 90 electrons per SAQD [39,44]. This increases the charge at z_ℓ as compared to sample U under otherwise identical conditions and decreases the electric field $|F(z_u)|$ at the site of the upper layer accordingly and with it the emission rate. τ_- measured for D_{lu} , on the other hand, is larger than that found for U for all measurement voltages. This indicates that further charge, in addition to the charge in the s -state of the SAQDs of layer ℓ is present, which decays on a timescale similar to that of the charge in the s_2 state of layer u . Possibly, higher energy states of the SAQDs are occupied. To be consistent with the measurements, this transient storage, which again decreases the electric field at z_u , must have a time scale of the order of τ_- but much smaller than τ_+ . We note that at these bias voltages, z_ℓ is outside the space charge region, and free electrons can partially screen the charge stored in layer ℓ . The additional charge present in layer ℓ furthermore increases the potential energy of layer u , see Fig. 1 for an illustration. This decreases the capture rate for this layer and explains the shift of the $\tau_\pm$ maximum values to larger V_m as compared to those of U.

In the interval $-0.6 \text{ V} \geq V_m \geq -1.0 \text{ V}$, both time constants measured in the D_{lu} configuration drop with decreasing V_m , showing a remarkable kink at $V_m = -0.8 \text{ V}$: No signs of such a kink are visible in $\tau_\pm(V_m)$ of sample U, albeit this emission can only be detected for $V_m \geq -0.8 \text{ V}$. The Poisson-Schrödinger calculations show that in this regime, the end of the space charge region z_{dep} passes through z_ℓ , see Fig. 3(c). Screening of the charges in layer ℓ by conduction band electrons vanishes with decreasing voltage, and the coupling of the charge therein to layer u (prolongation of $\tau_\pm$) increases. We thus interpret the kink as the transition point between two opposite effects, namely the decrease of the time constants by the increasing electric field as V_m is decreased, and their increase by the removal of the screening of layer ℓ .

For $-1.0 \text{ V} \geq V_m \geq -1.3 \text{ V}$, the time constants increase with decreasing V_m . Here, layer ℓ begins to dominate the capacitance transients, and the increase of $\tau_\pm$ originates from its rapidly decreasing capture rate. The rates observed in the configurations D_ℓ and D_{lu} are almost identical. We note that the $\tau_\pm(V_m)$ functions from L are shifted by $+0.2 \text{ V}$ with respect to D_ℓ due to the slightly different sample layouts. In the range $-1.3 \text{ V} \geq V_m \geq -2 \text{ V}$, however, τ_- of the D_{lu} configuration is smaller than for the configuration D_ℓ up to a factor of 2. In this V_m interval, the residual emission from the s_1 states in layer u is expected to contribute directly to the capacitance

transient. However, we find no indication for a tri-exponential decay. Estimates based on the rate equation model for a single layer indicate that the time constant of the emission from s_1 of the upper layer is indistinguishable from τ_+ in this regime within our resolution. This is in tune with the weight of τ_+ in this regime being twice the weight of τ_- , while for single-layer emission the weights are identical [38]. Thus we exclude emission from the s_1 states of layer u as a possible origin for this reduced time constant. Instead, we suggest that it is a manifestation of *cascade coupling*, i.e., electrons emitted by layer u get recaptured transiently by layer ℓ (either its wetting layer or its SAQDs) before they move on to the reservoir. Such a recapture could occur via p states, or empty s states of adjacent SAQDs. This increases the time-averaged charge felt by an SAQD with two occupied s states. Its potential is therefore increased leading to a decreased time constant, in particular τ_- , since on this timescale, electrons still get emitted by layer u .

In order to substantiate the validity of this interpretation, we look at the quantitative values which follow therefrom. As has been shown elsewhere, the capacitance transient of single-layer structures can be described accurately by a rate equation model [37]. For the present situation, a maximum occupancy of two electrons per dot is considered, occupying levels s_1 and s_2 of the two layers in sample D with state-specific rates [45] $e_k^{i \rightarrow j} \equiv e_k^{ij}$ and $c_k^{j \rightarrow i} \equiv c_k^{ji}$. They are bias voltage dependent, and we model them empirically by the exponential functions [37]

$$\begin{aligned} e_k^{ij}(V) &= \exp(\alpha_k^{ij} \cdot V + \beta_k^{ij}) s^{-1}, \\ c_k^{ji}(V) &= \exp(\gamma_k \cdot V + \chi_k^{ji}) s^{-1}, \end{aligned} \quad (3)$$

with the parameters α_k^{ij} and β_k^{ij} for emission and γ_k as well as χ_k^{ji} for capture. Here, the index $k \in \{\ell, u\}$ denotes the layer and $i, j \in \{0, 1, 2\}$ are the corresponding occupation numbers of one SAQD. Since the processes in p states are too fast to be measured, we do not have values for their input parameters and exclude them here. The occupation dynamics of each layer in response to a bias pulse can be obtained by solving the system of rate equations

$$\begin{aligned} \dot{n}_k^0 &= -c_k^{01} \cdot n_k^0 + e_k^{10} \cdot n_k^1, \\ \dot{n}_k^1 &= -c_k^{12} \cdot n_k^1 + e_k^{21} \cdot n_k^2 + c_k^{01} \cdot n_k^0 - e_k^{10} \cdot n_k^1, \\ \dot{n}_k^2 &= c_k^{12} \cdot n_k^1 - e_k^{21} \cdot n_k^2. \end{aligned} \quad (4)$$

Here, $n_k^j \in [0, 1]$, $\sum_j n_k^j = 1$, denote the probability of SAQDs in layer k with the occupation number j , and the dotted symbols denote their time derivative. The parameters for all samples/configurations of D are extracted by least-squares fitting the simulated $\tau_\pm(V_m)$ to the measured functions, as shown by lines in Fig. 3(b) with fit parameters summarized in Table I.

Regarding the simulations for the D_{lu} configuration, we approximate the SAQDs hosting two electrons each by a homogeneous sheet charge density ρ_k per layer and compute its effect on the electric field $dF(z_k)$ at the second layer q using the Poisson-Schrödinger solver [43]. Here, the WLs are included by an InAs layer of 0.6 nm width. The effect of charge within the WL or higher SAQD states was introduced

TABLE I. Parameters obtained by fitting Eq. (3) to data from sample L, U ($V_p = 0.4$ V), and sample D in configurations D_ℓ ($V_p = -1$ V) and $D_{\ell u}$ ($V_p = 0.4$ V, $V_m > -0.5$ V).

Sample	α_k^{10} (V^{-1})	β_k^{10}	α_k^{21} (V^{-1})	β_k^{21}	γ_k (V^{-1})	χ_k^{01}	χ_k^{12}
L	-1.24	4.66	-0.72	7.77	11.94	18.39	20.12
U	-0.95	6.01	-0.91	8.92	20.27	8.55	10.62
D_ℓ	-1.46	4.07	-0.67	7.58	5.56	12.81	14.70
$D_{\ell u}$	-1.75	5.46	-1.41	8.17	13.59	6.07	7.70

by using the fit parameters obtained from configuration $D_{\ell u}$ for $V \geq -0.5$ V. Addition of electrons to the lower layer decreases $|F(z_u)|$ and increases z_{dep} . Thus the triangular-shaped tunnel barrier of the upper layer gets broader and its emission rates decrease, see also the scheme in Fig. 1. For capture of diffusing electrons originating from the back contact [45], an increased depletion width leads to a decrease of the capture rate, as in response to a more negative bias voltage. The resulting charge-induced shifts $\Delta F(z_u)$ can be compensated by the bias voltage. Likewise, $\Delta F(z_\ell)$ in response to the occupancy of the upper layer was calculated. Here, both $|F(z_\ell)|$ and z_{dep} increase as the upper layer gets filled.

The electrostatic coupling is integrated into the rate equation model for the transfer rates of layer k by substituting the voltage V in Eq. (3) accordingly. Since the electric field $F(z_u)$ determines the upper layer emission rates, we use the Poisson-Schrödinger solver to calculate $dF(z_u, \rho_\ell)$ [see Fig. 3(b) and Ref. [38]] and then determine the bias voltage $V(\rho_\ell)$ by multiplication with z_{dep} . The bias voltage $V(\rho_\ell) = V_0 + (dV/d\rho_\ell)\rho_\ell$ is then used in the rate equation model, where $dV/d\rho_\ell$ takes the role of a coupling function. Likewise, $V(\rho_u)$ is computed for the influence of charge in the upper layer on the electric field on the lower layer. The cascade coupling is incorporated into the rate equation model as well: for independent occupation probabilities of both layers over a time interval Δt , the net change in mean electron number of the upper layer,

$$\Delta n_u = (n_{u,1} + 2n_{u,2})|_t - (n_{u,1} + 2n_{u,2})|_{t+\Delta t} \quad (5)$$

yields the number of electrons available for recapture into layer ℓ . The fraction of these electrons that are actually captured is $\alpha \Delta n_u$, where α is the recapture probability. The captured electrons are redistributed into the unoccupied states of layer ℓ in order of increasing energy, and the updated occupation probabilities $n_{\ell,1}$ and $n_{\ell,2}$, capped at full occupancy, serve as initial conditions for the subsequent time step. We note that the p and d states may contribute to the cascade coupling, but resolving these contributions would require improved time resolution or measurements at lower temperatures. The rate equation system was solved numerically by computing the time-dependent state distribution via the exponential of the transition matrix. The capacitance transient is then determined by

$$C(V, t) = \frac{\epsilon_r \epsilon_0 A \sqrt{qn_D}}{\sqrt{2[\epsilon_r \epsilon_0 (V_{bi} - V) - \rho_u(t)z_u - \rho_\ell(t)z_\ell]}}, \quad (6)$$

where V_{bi} denotes the built-in voltage of the Schottky barrier.

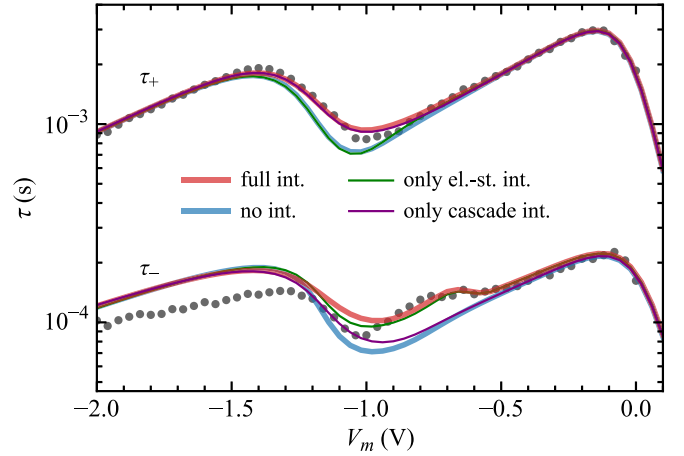


FIG. 4. Simulated $\tau_{\pm}(V_m)$ with full (red line), without (blue line), with only electrostatic (green), and with only cascade interaction (purple) in comparison to the experimentally determined time constants of the $D_{\ell u}$ configuration (dark gray circles). τ_+ datapoints of full interaction and only cascade interaction as well as no interaction and only el.-st. interaction are almost identical.

In Fig. 4, the measured functions $\tau_{\pm}(V_m)$ from configuration $D_{\ell u}$ are shown together with the results of the simulations in the absence of couplings, for only electrostatic interactions and for only the coupling by emission and recapture. The fit comprising both coupling mechanisms provides good agreement with the measurements. For the fit, a recapture probability $\alpha \approx 0.1$ into s states for cascade coupling and an enhancement factor of 12 for the charge in layer ℓ towards s_2 emission from layer u were assumed, the latter reflecting the additional charge in the WL and in higher SAQDs states. Poisson-Schrödinger calculations reveal an initial charge of ≈ 15 electrons per SAQD within the WL when a preparation voltage of 0.4 V is applied. Adding the two electrons from the s states and up to six electrons which may occupy the p states sums up to 23 electrons per SAQD contributing to the electrostatic coupling, consistent with the enhancement factor.

It emerges that both coupling mechanisms are required for good agreement with the measurements. The electrostatic contribution explains the measurements well for $V_m \geq -1$ V for the faster s_2 emission. The cascade coupling term, on the other hand, fails to reproduce the enhancement of τ_- in the range $-1 \text{ V} \lesssim V_m \lesssim -0.5 \text{ V}$. These contributions are readily comprehensible within our above interpretation. The model fails, however, to explain the reduction of τ_- at low V_m , which is in tune with the interpretation given above in terms of charge present in layer ℓ beyond their s states.

IV. SUMMARY AND OUTLOOK

Coupling between two layers of self-assembled quantum dots separated by 200 nm is detected and studied by transient capacitance spectroscopy with a time resolution of $\approx 9 \mu\text{s}$. The transients show a biexponential decay, the time constants of which contain information on the capture and emission dynamics of the two layers which are influenced by interlayer interactions. Our data are consistent with a model comprising electrostatic interactions between the layers, in combination

with cascaded emission of electrons from the upper layer via the lower layer into the drain contact. At high bias voltages, the lower wetting layer is partially occupied and couples electrostatically to the electrons in the SAQDs of the upper layer. At intermediate voltages where the wetting layers are empty, the voltage dependence of the time constants suggests the presence of cascade coupling, where electrons emitted from the upper SAQDs are transferred to the reservoir via states in the lower layer. At low bias voltages, finally, we observe a reduction of the smaller time constant in the double layer system as compared to the single layer sample, the origin of which has been tentatively attributed to cascade coupling as well. Processes involving higher SAQD states as well as dynamics provided by the wetting layer are too fast to be resolved at 77 K. In particular the p state dynamics may become accessible at lower temperatures. In addition, a method to suppress electronic states in the wetting layer could be used in future devices to discern from WL related sheet charge contributions [39]. Furthermore, it may be possible to identify such coupling

phenomena in layered SAQD devices like those mentioned in the introduction. Finally, our model simulations are limited by the projection of the three-dimensional samples onto one dimension. Improvements may be possible in this respect by extending the simulations to three-dimensional self-consistent band structure calculations.

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DATA AVAILABILITY

The data that support the findings of this article are openly available [46].

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