Highly symmetric and tunable tunnel couplings in InAs/InP nanowire heterostructure quantum dots

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Abstract
We present a comprehensive electrical characterization of an InAs/InP nanowire (NW) heterostructure, comprising of two InP barriers forming a quantum dot (QD), two adjacent lead segments and two metallic contacts. We demonstrate how to extract valuable quantitative information of the QD. The QD shows very regular Coulomb blockade resonances over a large gate voltage range. By analyzing the resonance line shapes, we map the evolution of the tunnel couplings from the few to the many electron regime, with electrically tunable tunnel couplings from $<1 \mu eV$ to $>600 \mu eV$, and a transition from the temperature to the lifetime broadened regime. The InP segments form tunnel barriers with almost fully symmetric tunnel couplings and a barrier height of $\sim 350$ meV. All of these findings can be understood in great detail based on the deterministic material composition and geometry. Our results demonstrate that integrated InAs/InP QDs provide a promising platform for electron tunneling spectroscopy in InAs NWs, which can readily be contacted by a variety of superconducting materials to investigate subgap states in proximitized NW regions, or be used to characterize thermoelectric nanoscale devices in the quantum regime.

Keywords: InAs/InP, nanowire, quantum dot, tunnel barrier, electron tunneling spectroscopy, coulomb resonance line shape

(Some figures may appear in colour only in the online journal)
2. Results

2.1. Device fabrication

The InAs/InP heterostructure NWs were grown by gold assisted chemical beam epitaxy [15] and have a diameter of 50 ± 5 nm, depending on the size of the gold seed particle. The QD is formed on an InAs segment of length \( s \approx 19 \text{ nm} \), bounded by two InP barriers of width \( \ell_1, \ell_2 \approx 5.5 \text{ nm} \), as shown in figure 1. The dimensions of the InP barriers were determined in a transmission electron microscopy (TEM) analysis of NWs of the same growth. The device was fabricated on a degenerately p-doped silicon substrate acting as a global back gate with a 400 nm thick SiO\(_2\) capping layer. The electrical contacts to the NW are made of titanium/gold films with a thickness of 5 nm/65 nm. Before evaporating the contact material, the native oxide of the NWs is etched with an (NH\(_4\))\(_2\)S\(_2\)H\(_2\)O solution [41]. A false color scanning electron microscopy (SEM) image of a typical device is shown in figure 1. In contrast to crystal-phase defined InAs QDs, the two InP segments can be imaged directly by standard SEM techniques with an in-lens detector [29].

We explicitly refer to the regions of bare InAs between the QD and the source or drain contact as the LSs. The lead segment LS\(_1\) between the QD and the source contact is \( L_1 \approx 350 \text{ nm} \), while the lead segment LS\(_2\) between the QD and the drain contact is \( L_2 \approx 600 \text{ nm} \). The QD and the LSs are tuned simultaneously by the back gate voltage \( V_{BG} \), which shifts the conduction band edge \( E_{CB\text{E}}(V_{BG}) \), relative to the Fermi energy, \( E_F \), to higher or lower values. For later, we use \( \phi(V_{BG}) = E_F - E_{CB\text{E}}(V_{BG}) \).

The inset of figure 1 shows a TEM image of the epitaxially defined QD region in a similar NW. The two InP segments, indicated by black arrows, act as tunnel barriers with a rectangular potential profile for electrons due to the atomically sharp transitions in the material composition. The barrier height depends on the band gap discontinuities and residual strain. For our NW geometry, the barrier height is predicted to be \( V_0 \approx 400 \text{ meV} \) [34], providing a strong confinement to the electrons in the axial direction.

All measurements were performed in a dilution refrigerator with a base temperature of \( ~30 \text{ mK} \). We apply a DC voltage to the source electrode to correct for small offsets \( V_{DC} \approx 50 \mu\text{V} \) and superimpose an AC voltage of typically \( 1 \mu\text{V}_{\text{rms}} \) for lock-in detection, while the drain electrode is...
grounded and used for the current (I) measurement. The differential conductance \( dI/dV_{SD} = I_{AC}/V_{AC} \) was measured using standard lock-in techniques.

### 2.2. Characterization of the QD

Figure 2(a) shows \( dI/dV_{SD} \) as a function of \( V_{SD} \) and \( V_{BG} \). We observe regular, stable, and reproducible Coulomb diamonds (CDs) over the large backgate range of 30 V, corresponding to the addition of \( \sim 124 \) electrons. At \( V_{BG} \approx 1 \) V, the number of electrons on the QD is close to zero, i.e. \( N \approx 0 \). By increasing \( V_{BG} \), electrons are added to the QD sequentially, which brings the QD into the many electron regime. For the measurement sequence shown in figure 2(a), the maximum number of electrons on the QD is \( N \approx 124 \). When increasing \( V_{BG} \) beyond 40 V, thermal activation of carriers across the tunnel barriers begins to considerably contribute to the transport.

According to the constant interaction model \([42]\), assuming two-fold spin-degenerate orbitals, the energy required to add an electron to a QD with an even electron configuration is given by the addition energy \( E_{\text{add}} = E_C + \Delta \), with \( E_C = e^2/C_Z \) the charging energy, the total capacitance \( C_Z \) of the QD, and \( \Delta \) the single particle energy spacing. To add a second electron to the same QD orbital requires \( E_{\text{add}} = E_C \). This gives rise to an alternating even–odd pattern of large and small CDs, characteristic for spin-degenerate QD states, and allows one to extract the corresponding energy scales. A region of the CDs shown in figure 2(b) exhibits a clear even–odd pattern with \( E_{\text{add}} = 5.5 \) meV and \( E_C = 4.2 \) meV, as indicated by the white arrows. From the difference between \( E_{\text{add}} \) and \( E_C \), we find \( \Delta = 1.3 \) meV, consistent with \( \Delta \approx 1.6 \) meV from the corresponding excited state (ES) resonances outside the CDs, pointed out by white arrows.

In figure 2(c) we plot \( E_{\text{add}} \) as a function of \( N \) for the full \( V_{BG} \) range of figure 2(a). We find an overall decrease in \( E_{\text{add}}(N) \) for increasing \( N \) due to changes in the QD capacitance by electron–electron interactions \([43]\). From the very regular even–odd pattern in the gate range indicated by the blue box in figure 2(a), we extract \( \Delta(N) \), as shown in the inset of figure 2(c). We find that \( \Delta \) strongly scatters and assumes values in between 0.2 and 4 meV, suggesting that only single levels contribute to the transport.

In addition to the QD ES resonances, we find several other features outside of the CDs that cannot be attributed to the energy spectrum of the QD. For example, the resonances indicated by orange arrows in figure 2(b) are due to a non-constant DOS in the LSs, forming as standing waves in the LSs. Since these waves are strongly reflected at the InP barrier, the widths of these states are determined mostly by the coupling to the source and drain contacts, respectively. In addition, we find negative differential conductance (NDC) throughout the entire gate range, which we attribute to the simultaneous tuning of the QD and the LSs with different lever arms. We note that the NDC is more prominent in the few electron regime where the carrier concentration is low.
The NDC supports our notion that the DOS in the LSs is not constant, which is typical for NW QD devices with semiconductor leads [30].

2.3. Resonance line shapes

In this section, we extract the total tunnel coupling of the QD, $\Gamma$, and the electron temperature in the LSs, $T$, from the CB resonances. The total tunnel coupling, $\Gamma = \Gamma_1 + \Gamma_2$, is given by the individual couplings to the source and drain leads, $\Gamma_1$ and $\Gamma_2$, respectively. In the case of an ideal measurement setup, the line shape only depends on $\Gamma$, $T$ [44], and the asymmetry $A = \Gamma_1/\Gamma_2 \geq 1$ [45, 46]. However, there are also extrinsic broadening mechanisms, such as noise in the source and drain contacts, and on the gate, as well as the applied AC voltage.

For our analysis, we assume that only a single QD level contributes to the transport, i.e. $eV_{AC} < 4k_BT$, $\Gamma$. By tuning $E_{CB}$ with $V_{BG}$, we can access three different regimes: thermally broadened ($\Gamma$, $eV_{AC} < 4k_BT$), lifetime broadened ($4k_BT$, $eV_{AC} \ll \Gamma$), or a combination of both ($eV_{AC} \ll \Gamma \approx 4k_BT$). These three regimes are summarized in figures 3(a), (c), and (e), where the lifetime broadening is indicated by the width of the blue QD levels and the thermal broadening by the width of the orange Fermi–Dirac distribution in the LSs.

We model the line shape of the CB resonances with the assumption that the DOS in the LSs is constant and discuss effects due to a non-constant DOS later. For a single energy level, the line shape of a conductance resonance is described by a resonant tunneling model [44, 47, 48]:

$$I = \frac{e}{h} \int T_{QD}(E)\left[f_s(E) - f_D(E)\right]dE,$$

where $g = 1$ is the number of independent parallel transport channels, $T_{QD}(E) = (1/\Gamma_2)/(|\Delta|E^2 + \Gamma_2^2/4)$ the Breit–Wigner (BW) transmission function [47] with $\Delta E = E - E_0$ the detuning from the CB resonance centered at $E_0$, and $f_{s/D}(E) = 1/(1 + \exp(E + eV_{s/d})/k_BT)$ the Fermi–Dirac distributions in the LSs. $dI/dV$ is calculated numerically.

The contribution of $V_{AC}$ is accounted for by evaluating equation (1) for a sinusoidal $V_S$ that also electrically gates the QD. If not chosen properly, $V_{AC}$ can mask the ‘true’ resonance and the measured resonance width is then given by $V_{AC}$.

In the regime where the broadening is mainly due to temperature, $\Gamma \ll 4k_BT \ll \Delta$, equation (1) reduces to $G/G_{max} = \cos^2(\Delta E/2k_BT)$, where $G_{max} = e^2/h \cdot \pi/2k_BT \cdot (\Gamma_1 \Gamma_2/\Gamma)$ [44]. In this limit, $T$ can be extracted from the full-width at half maximum (FWHM) of the resonance by FWHM $\approx 3.5k_BT$.

In the limit where the broadening is mainly due to the electron lifetime on the QD, $4k_BT \ll \Gamma \ll \Delta$, equation (1) reduces to the BW formula [47] $G/G_{max} = (\Gamma/2)^2/(\Delta E^2 + (\Gamma/2)^2)$ with $G_{max} = e^2/h \cdot 4\Gamma_1\Gamma_2/\Gamma^2$. In this limit, FWHM $\approx 4k_BT$ is the 10%–90% width of the Fermi–Dirac distribution.

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Gamma and A determines the maximum conductance $G_{max} = e^2/h \cdot 4A/(1 + A)^2$.

2.4. Evolution of the resonance line shapes

We now investigate how the line shapes of the resonances evolve with $V_{BG}$ and the bath temperature, $T_{bath}$. Figures 3(b), (d), and (f) show high resolution CB resonance measurements in the three broadening regimes. To show the evolution of $\Gamma$, each of the three CB resonances was fit with the expressions for a thermal, BW, and the convolution line shape, described by equation (1). From the convolution fit, we extract $\Gamma_1$, $\Gamma_2$, $T$, and their corresponding standard error of the individual fits, shown as error bars in figures 3(g) and 4.7

Figure 3(b) shows a CB resonance near depletion ($N \approx 10$) at $V_{BG} = 6.6$ V, measured with $V_{AC} = 0.1$ mV. The convolution line shape agrees very well with the experiment, as does the pure thermal broadening line shape, but not the BW line shape. In this regime, the conduction band edge of the LSs is near the Fermi

7 This error bar does not account for potential experimental errors in consecutive experiments.
level (ϕ ≪ V₀) and the electrons are strongly confined by the large tunnel barriers, such that the width of the Coulomb resonance is mostly determined by the electron temperature and not by the QD lifetime. Only in this regime, we can accurately determine the electron temperature of the LSs. From the convolution fit, the extracted total tunnel coupling, asymmetry, and electron temperature are Γ = 2.51 ± 0.07 µeV, A = 1.05 ± 0.04, and T = 50.5 ± 0.2 mK, respectively. We see that T is somewhat higher than the bath temperature (Tᵇath = 30 mK), probably due to noise and radiation due to insufficient filtering. Since T is not expected to change with VBG, we set T = 50.5 mK for the following analysis of data at the same Tᵇath.

For the resonance at VBG = 13.5 V (N ≈ 50) a transition from the thermally to the lifetime broadened regime begins. As shown in figures 3(c) and (d), only the convolution line shape fits the data well. From the convolution fit, with T = 50.5 mK and V⟩ = 0.25 µeV, Γ = 18.1 ± 0.4 µeV and A = 6.2 ± 0.2 were extracted from the fit. Therefore, this resonance is in the regime where the lifetime and thermal broadening contributes equally significantly with Γ ≈ 4k_BT.

By increasing the gate voltage further, the Coulomb resonances transition into the lifetime broadened regime with Γ ≫ 4k_BT. This can be seen for the resonance in figure 3(f) at VBG = 24.99 V (N ≈ 100), where the data agrees very well with the convolution fit, as well as with the BW fit, with T = 50.5 mK and V⟩ = 1 µV fixed. From the convolution fit, we extract Γ = 52.5 ± 0.1 µeV and A = 7.2 ± 0.1, which shows that the resonance is mostly lifetime broadened (Γ ≫ 4k_BT).

For each of the three resonances, the temperature dependence of the CB resonances was investigated, as shown in figure 3(g). We used the convolution fit with Γ₁ and Γ₂ fixed at the values determined at Tᵇath = 30 mK, to extract T for a series of different Tᵇath. For low Tᵇath, the CB resonances are either thermally broadened for Γ ≪ 4k_BT, lifetime broadened for 4k_BT ≪ Γ, or a combination of the two for Γ ≈ 4k_BT; as discussed in the previous section. For bath temperatures between 30 and 60 mK, the extracted T remains constant. As we increase Tᵇath beyond 60 mK, T for two resonances (cyan and orange) increases with a slope of 1.00 ± 0.05, in agreement with the thermally broadened regime. This is indicated by the dashed black line with a slope of 1. However, for the blue resonance, which is mostly lifetime broadened, the slope is 1.2 ± 0.1, likely due to the resonance not fully transitioning into the temperature broadened regime. These experiments show that the electron and phonon system equilibrate at ∼100 mK and that InAs/InP heterestructure QDs can be used as in situ thermometers. In contrast to typical CB thermometers [49, 50], integrated QDs form an integral part of the device, which does not require thermal coupling to a separate device. We note that a series of thermal cycling takes roughly one week during which we did not observe any charge rearrangements, demonstrating a unique stability of this type of QD. Only tuning VBG on the scale of several tens of volts results in a shift of the CB spectrum, which is reproducible and likely due to significant charging of substrate states.

2.5. Properties of the tunnel barriers

By investigating the functional dependence of the total tunnel coupling Γ and the asymmetry A on VBG, we estimate the height and symmetry of the tunnel barriers formed by the InP segments. By fitting the CB resonances with equation (1) and using the previously determined T = 50.5 mK, we extract Γ and A as a function of VBG, as shown in figures 4(a) and (b), respectively. The red data points correspond to the CB resonances from figures 3(b), (d), and (f) measured with a high resolution in VBG, while the black data points stem from resonances selected from a large gate sweep (ΔN ≈ 150) over 50 V measured with a lower resolution.

Γ(VBG) is plotted in figure 4(a) and shows a systematic increase of Γ with increasing VBG. Close to full depletion, we find a tunnel coupling of Γ ≈ 1 µeV, which increases up to ∼600 µeV for VBG = 42 V. Comparing the dependence of Γ(VBG) to a resonant tunneling model allows us to estimate V₀. For this, we assume that an electron bounces back and fourth in the InAs segment between the two InP barriers at an attempt frequency ν and escapes through either of the barriers with a probability given by the rectangular tunnel barriers. Consequently, the total tunnel coupling Γ as a function of VBG can be described by [51]:

$$\Gamma(V_{\text{BG}}) = 2/\nu \left(1 + \frac{V_{\text{BG}}}{V_0} \sinh^2\left(\frac{\nu}{2}\right)\right)^{-1}$$
with \( \kappa(\phi) = \sqrt{2m_\text{ep}(V_0 - \phi(V_{BG}))}/\hbar^2 \), \( m_\text{ep} = 0.08m_e \), the effective electron mass in the InP segments [52], \( \phi(V_{BG}) = \varepsilon \alpha_{LS}(V_{BG} - V_p) \), \( \alpha_{LS} \) the lever arm of the LSs, \( V_p \) the pinch-off gate voltage, \( \nu = \phi(V)/2\pi \) the attempt frequency with Fermi velocity \( v_F = \sqrt{2m_\text{InAs}/\hbar^2} \), and \( m_\text{InAs} = 0.04m_e \), the effective electron mass in wurzite InAs [53]. The values for the length of the InP segments and the QD were taken from the TEM analysis, with \( \ell = \ell_{1/2} = 5.5 \text{ nm} \) and \( s = 19.0 \text{ nm} \), respectively.

From the best fit of equation (2) to \( \Gamma(V_{BG}) \) (solid blue), we obtain the free parameters \( V_0 = 350 \pm 50 \text{ meV} \), \( V_p = 3 \text{ V} \), and \( \alpha_{LS} = 0.0053 \). \( V_0 \) is in good agreement with the calculated literature value of \( V_0 = 400 \text{ meV} \) for strained InP in InAs NWs with our geometry [34]. The upper and lower solid gray lines are obtained using the same parameters and \( V_0 = 300 \text{ meV} \) and \( V_0 = 400 \text{ meV} \), respectively. \( V_p \) agrees very well with the first CB resonances and \( \alpha_{LS} \) is 4.5 times smaller than the lever arm to the QD, in qualitative agreement with the LSs being longer than the QD.

Next, we investigate the asymmetry \( A \) as a function of \( V_{BG} \) in figure 4(b). The values of \( A \) scatter seemingly random between 1 and 8 for \( V_{BG} > 10.5 \text{ V} \). However, for \( V_{BG} < 10.5 \text{ V} \), \( A \approx 1 \) is constant, indicating highly symmetrical tunnel barriers. These characteristics of \( A \) can be understood qualitatively by the following argument. The modulation of the DOS in the confined LSs is determined by the single particle level spacing in the LSs, \( \Delta_{LS} \), and the broadening of the energy levels in the LSs, \( \Gamma_{LS} \). At \( E_F \), \( \Delta_{LS} = \pi/h v_F/\ell_{1/2} \) for a parabolic dispersion relation and thus \( \Delta_{LS} \sim \Delta/10 \). In addition, the strong coupling between the LSs and the source or the drain contact gives rise to a larger \( \Gamma_{LS} \) than for the QD. With increasing \( V_{BG} \), \( V_p \) also increases and we suspect that for \( V_{BG} > 10.5 \text{ V} \), \( \Delta_{LS} > \Gamma_{LS} \), leading to a weaker overlap between the energy levels and thus to a stronger modulation of the DOS in the LSs. In contrast, for \( V_{BG} < 10.5 \text{ V} \), \( \Delta_{LS} \) decreases and the energy levels in the LSs overlap stronger, resulting in a weaker modulation of the DOS. Consequently, in the low gate regime, \( A \) reflects the asymmetry of the tunnel barriers \( A \approx 1 \), which are essentially equal in length and height.

3. Summary and conclusion

In summary, we present an in-depth characterization of a QD formed by InP tunnel barriers and connected to metallic contacts via NW LSs. For this system we demonstrate a nearly depletible QD with CDVs that are exceptionally robust against charge rearrangements over a large gate range of 30 V, corresponding to \( \sim 124 \) electron states, and several months measurement time. By analyzing the line shapes of the CB resonances, we find a continuous transition from the lifetime to the thermally broadened regime and extract the electron temperature in the LSs. The QD shows a systematic and tunable increase in the tunnel coupling, based on which we estimate the conduction band edge offset between the InAs and the InP segments as \( V_0 = 350 \pm 50 \text{ meV} \). The InP segments act like ideal tunnel barriers with an asymmetry of \( A = \Gamma_1/\Gamma_2 \approx 1 \), as targeted in the crystal growth. This is found for low \( V_{BG} \), where the modulation of the DOS in the LSs is negligible, while at larger \( V_{BG} \) the transport is modulated by the NW lead states. In conclusion, we demonstrate that integrated InAs/InP QDs are a promising platform for quantitative in situ electron tunneling spectroscopy and thermometry for future superconducting hybrid devices and other electronic and thermoelectrical applications.

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Author Contributions

FT fabricated the device and performed the measurements. FT, AB, MN, and GF analyzed the data. CJ supported the fabrication and performed several electrical characterization measurements on different growth batches of the InAs/InP NWs. LG fabricated, measured, and analyzed a similar device. GF performed measurements for a similar device that FT and CJ fabricated. FR, VZ, and LS developed the nanowire structure. CS and AB planned and designed the experiments, and participated in all discussions. All authors contributed to the manuscript.

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