Characterization of electrostatically defined bottom-heated
InAs nanowire quantum dot systems

Sven Dorsch, Sofia Fahlvik and Adam Burke

Solid State Physics and NanoLund, Lund University, SE-22100 Lund, Sweden
* Author to whom any correspondence should be addressed.
E-mail: sven.dorsch@ftf.lth.se and adam.burke@ftf.lth.se

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Abstract

Conversion of temperature gradients to charge currents in quantum dot systems enables probing various concepts from highly efficient energy harvesting and fundamental thermodynamics to spectroscopic possibilities complementary to conventional bias device characterization. In this work, we present a proof-of-concept study of a device architecture where bottom-gates are capacitively coupled to an InAs nanowire and double function as local joule heaters. The device design combines the ability to heat locally at different locations on the device with the electrostatic definition of various quantum dot and barrier configurations. We demonstrate the versatility of this combined gating- and heating approach by studying, as a function of the heater location and bias, the Seebeck effect across the barrier-free nanowire, fit thermocurrents through quantum dots for thermometry and detect the phonon energy using a serial double quantum dot. The results indicate symmetric heating effects when the device is heated with different gates and we present detection schemes for the electronic and phononic heat transfer contribution across the nanowire. Based on this proof-of-principle work, we propose a variety of future experiments.

1. Introduction

Thermoelectric (TE) materials enable the conversion of temperature gradients to electricity and are in principle capable of power generation and active cooling, but in practice, however, are often held back by low figure of merits, thus limiting efficiencies [1–3]. Nanoscale semiconductor devices, instead of relying on intrinsic material properties, allow engineering of favourable electronic and thermal device properties and thus have led to various concepts for efficient thermal energy harvesting [3–6].

A conventional two-terminal heat engine consists of a TE device coupled to two thermal reservoirs at different temperatures [7]. The figure of merit of such heat engines scales with the Seebeck coefficient $S$ of the device and the ability to maintain a large temperature difference between reservoirs. Here, nanowires can yield advantages compared to bulk materials in the form of an increased $S$, and a reduction of the phononic contribution to the thermal conductivity [2, 5]. Maximum TE efficiency of a heat engine, however, is expected only when the device acts as perfect energy filter and requires further modification of the electronic structure of the device [1, 8, 9].

Experimentally, ideal energy filters are realized through quantum dots (QDs) [10–15] or single-molecular junctions [16, 17] and heat engines reaching high efficiencies were demonstrated in heterostructured InAs/InP nanowire QDs [18–20]. Thermocurrent measurements across QD heat engines are further applicable for thermometry [21] and spectroscopy [22–24] purposes and the controllable level structure of coupled multi-QD systems enables the realization of three-terminal energy harvesters, where charge and heat flow are decoupled [4, 25–28].

Nanowire-based, heated TE QD devices are commonly built with epitaxially-defined InAs/InP QD structures [18, 20, 28]. Such epitaxially defined QD systems offer large single-particle energies and symmetric tunnel couplings at the cost of a static barrier structure and complex control over the tunnel couplings [29]. TE devices further require a heater with a large, local heating efficiency, controlled and...
Figure 1. Device and heater characterization. (a) Scanning electron micrograph of the device and schematic illustration of the experimental setup. (b) $I_{SD} - V_{SD}$ curve of the device at $V_{SD} = 1$ V showing ohmic behavior. (c) Thermocurrent $I_{th}$ at $V_{SD} = 0$ V as a function of the heating bias $dV_R$. Inset: current as a function of $dV_L$, $dV_M$ and $dV_R$.}

continuous tunability of the temperature gradient and compatibility with the QD gating technique [30]. In addition to these requirements, symmetric alignment of the heater with the QD system is important for the controlled definition of temperature gradients and a requirement for purely phonon-absorption based three-terminal energy harvesters [28]. Accurate alignment of a side- or top-heater electrode to epitaxially defined QD structures in nanowires remains, however, technically challenging.

In this proof-of-principle work we use thin InAs nanowires, which have been demonstrated to form high quality electrostatically defined QD structures and single particle energies of around 1 meV in sidegated devices [31], with a combined bottom-gate and bottom-heater device architecture. These devices combine the flexibility to form variable barrier and multi-barrier structures [32] with the ability to heat localized at different positions along the nanowire axis, engineering different temperature gradients. Our approach naturally results in a symmetric heating effect of the heaters with respect to electrostatically induced barriers. In the following, we experimentally study the TE effect across the barrier-free nanowire and QDs as well as phonon-assisted transport (PAT) and the TE effect on a double quantum dot (DQD) structure.

2. Experimental configuration and initial characterization

2.1. Device fabrication

Arrays of 50 nm wide Ti/Au (2/8 nm) gate stripes with a center-to-center distance of 100 nm were defined atop a thermally oxidized silicon substrate by a combination of electron beam lithography (EBL) and thermal evaporation. Next the gate arrays were covered by an 8 nm HfO$_2$ layer via atomic layer deposition within an EBL exposed high-$k$ window. This allows the following deposition of thin, chemical beam epitaxy grown, wurtzite InAs nanowires (diameter 35–40 nm, grown in (111)B orientation), electrically insulated from the gate stripes, using a micromanipulator. The accurate position of suitable nanowires with respect to the gate arrays were identified in a scanning electron microscope and 600 nm spaced source (S) and drain (D) contacts to the nanowires were designed such that seven gate stripes (g1–g7, counted from S to D) are capacitively coupled to the enclosed nanowire segment. Then a nanowire contact half overlaps with the outer two gates (g1, g7) to allow full control over all enclosed nanowire sections and every third gate stripe (g1, g4, g7) is connectable on both ends and thus can act as local joule heater. In a final iteration of EBL in combination with Ni/Au (25/75 nm) thermal evaporation the nanowire contacts are defined and all active gates are connected to pre-patterned bondpads on the substrate. A tilt-angle SEM image of an exemplary device is shown in figure 1(a).

2.2. Measurement details

All measurements were performed in a dilution refrigerator and by fitting Coulomb peaks we find a base electron temperature of 90 ± 5 mK in the absence of heating on the device. Each measurement line has a cold-filtering resistance of 3.26 kΩ and the experimental setup is schematically illustrated in figure 1(a).
Yokogawa GS200 and Yokogawa 7651 voltage sources are used to bias all gates g1–7 (V_{g1–7}, V'_{g1–7}) and the source contact (V_{SD}). The current through the nanowire is detected with a HP 34401A voltmeter on the drain side after conversion to a voltage by a Femto DLPCA-200 I/V converter at a gain of 1 nA V^{-1} and an input impedance of 10 kΩ. We note that in this measurement configuration, electrons traveling from drain to source result in a positive current reading.

To locally heat the nanowire on the left (L), middle (M) or right (R) side, we apply a heating bias dV_{L/M/R} = V'_{1/4/7} - V'_{1/4/7} symmetrically around the voltage used to capacitively gate the nanowire (V'_{1/4/7} + V'_{1/4/7})/2 on the two ends of g1, g4 or g7, respectively. This leads to a heating current flow I_{L/M/R} through the gate stripe g1/4/7, which in turn acts as highly localized joule heater to the nanowire device, inducing a temperature gradient. For consistency in notation between all active bottom-gates we in the following denote the average voltage applied to the left/middle/right heater as V'_{1/4/7}.

For pure thermocurrent (I_{th}) measurements, we apply an effective, offset adjusted bias V_{SD} = 0 V to the source contact, correcting for an experimental setup based potential offset between the source and drain side. This offset was characterized by minimization of the bias driven current I_{SD} through the nanowire at a point of high conductance (Coulomb peak for QDs in section 3 and triple point for DQDs in section 4) by application of a small bias V_{SD}. We find a bias offset of −21 ± 2 μV which drifts slowly over time and use repeated control measurements throughout the data collection to exclude the possibility of larger shifts. All bias values V_{SD} are adjusted by −21 μV.

2.3. Nanowire and heater characterization

As a first step to prepare the device for the formation of QD and DQD structures, the nanowire is tuned to a conductive regime where the presence of unintentional barriers is excluded. Unintentional barriers are observed in the ungated device due to the conduction band roughness and low electron densities in thin InAs nanowires at low temperatures [33, 34]. Thus, we apply V_{1–7} = 1 V to enhance the nanowire conductivity and measure the resulting I_{SD} - V_{SD}-curve shown in figure 1(b). Observation of ohmic behavior with an overall circuit resistance R ≈ 61 kΩ around V_{SD} = 0 V confirms barrier free transport across the device. Consequently, in the following we always apply 1 V to all gates which are not actively used as either a barrier- or plunger gate.

In the barrier free regime of figure 1(b), we further demonstrate heater functionality by studying the TE effect across the nanowire by heating on the right side and measuring the resulting thermocurrent I_{th} as a function of the heater bias dV_{R}. The results are plotted in figure 1(c) and the short-circuit current indicates a net electron flow from drain to source, as sketched in the lower inset of figure 1(c), with thermocurrents reaching up to I_{th} = 300 pA at dV_{R} = ±200 mV. While a quantitative analysis of the Seebeck effect would require accurate thermometry, we consider the maximum magnitude of the thermocurrent and calculate the corresponding thermo-voltage ΔV_{th} ≈ 15 μV. As is discussed in section 3, at a heater bias of dV_{R} = 200 mV a maximum temperature difference between the left and right device contact of ΔT = |T_{L} - T_{R}| ≈ 0.5–1 K and an average temperature $\bar{T} = \langle T_{L} - T_{R} \rangle / 2 \approx 2.5$ K are realistic, which in turn yields an estimate for the upper bound of the Seebeck coefficient of $|S| = |ΔV_{th}/ΔT|_{I=0} \approx 15–30 \ μV K^{-1}$ [7, 35]. Here, T_{L} and T_{R} denote the electron temperatures on the source and drain side of the device, respectively. This estimate is comparable in magnitude to the Seebeck coefficient observed for InAs nanowire segments of comparable length at 4.2 K [36] and 10 K [37].

Figure 1(c) further yields information regarding heating symmetries. First, I_{th} is symmetric around dV_{R} = 0 and the sign of the heater current has no impact on the heating effect. Second, we independently measure I_{th} as a function of dV_{L}, dV_{M} and dV_{R}, which is shown in the upper inset of figure 1(c). A comparison of heating on the left and right bottom-heater reveals opposite signs of I_{th} but comparable magnitudes, suggesting a symmetric heating effect. In contrast, heating with the middle bottom-heater results in significantly lower I_{th} which indicates near uniform heating of the nanowire with a slightly increased temperature on the source- compared to the drain contact. This is attributed to a slight source and drain asymmetry with respect to g4.

3. Quantum dot thermoelectrics

Next, we introduce barriers to form a QD, which acts as sharp energy filter and in principle allows for highly efficient TE power conversion [1, 8, 9, 18, 19]. Further, in contrast to the barrier-free device configuration, fits to TE based thermocurrent measurements on QDs have in recent years been established as a reliable thermometry method without the need for additional device components [18, 20, 21, 28].

A small negative bias applied to g2 and g4 (V_{2} = −0.16 V, V_{4} = −0.2 V), electrostatically forms barriers in the nanowire conduction band. The resulting QD charge stability diagram as a function of the plunger gate voltage V_{S} is shown in figure 2(a) and the corresponding measurement configuration is schematically...
Figure 2. Thermocurrent in the left QD. (a) Charge stability diagram of a QD formed between g2 and g4. The differential conductance is saturated beyond ±18 nS for better visibility of all features. (b) Schematic illustration of the device configuration. (c) Thermocurrent measured along the red cutline in (a). The solid red line is a fit to the data. (d) Schematic illustration of the TE effect above $\mu_{SD}$ for an effective 1→2 charge transition of a QD. (e) Schematic illustration of the TE effect below $\mu_{SD}$ for an effective 0→1 charge transition of a QD. Black arrows in (d) and (e) indicate electrons with a set spin confined to the QD while gray arrows indicate available spin-selective states.

Illustrated in figure 2(b). We note that in the following, we refer to the configuration shown in figure 2(b) as left QD (QDL) as opposed to a QD formed on the right side (QDR) between g4 and g6 ($V_4 = -0.17$ V, $V_6 = -0.245$ V).

The charge stability diagram in figure 2(a) shows well-defined Coulomb blockade in a sequential tunneling regime and a clear single-particle energy spectrum. Regions of negative differential conductance are attributed to the non-uniform density of states in the quasi one-dimensional nanowire lead segments enclosing the QD. From the Coulomb diamond dimensions a gate lever arm \( \alpha_{QD}^3 = 0.58 \pm 0.01 \text{ eV V}^{-1} \) (QDR: \( \alpha_{QD}^5 = 0.48 \pm 0.01 \text{ eV V}^{-1} \)) is extracted. To study the TE effect across the QD, we first identify two consecutive crossings with a ground- to excited-statespacing of more than 1 meV. This choice ensures that for moderate heating only a single QD resonance contributes to thermocurrents.

With the reasonable assumption of conventional odd–even spin filling in our QD, we can then approximate the current through the system at the selected transitions by rate equations for a single spin-degenerate QD resonance [20, 38]. We further assume the QD to have an infinite charging energy, be weakly coupled to the reservoirs and neglect co-tunneling effects as well as lifetime and thermal QD level broadening. The QD resonance in our model system can be populated by 0, 1 or 2 electrons. Because of the spin degeneracy expected in experimental systems, every charge state transition can effectively be described by either the 0→1 or the 1→2 charge state transition of the model system. For an effective 0→1 charge state transition one then obtains

\[
I_{SD/th} = |e| \frac{2\Gamma_L \Gamma_R (f_R - f_L)}{\Gamma_R + \Gamma_L + \Gamma_{fL} + \Gamma_{fR}},
\]

where either a spin up or down electron can enter the QD. In contrast, only an electron with a fixed spin populates the resonance at any given time and thus the tunneling process out of the QD limits the current. Conversely, for an effective 1→2 charge state transition the current is described by

\[
I_{SD/th} = |e| \frac{\Gamma_L \Gamma_R (f_R - f_L)}{2(\Gamma_R + \Gamma_L) - \Gamma_{fL} - \Gamma_{fR}},
\]

where the tunneling process into the QD is spin selective but both a spin up or spin down electron can exit the resonance. Therefore, for an effective 1→2 charge state transition, the tunneling process into the QD limits the current. In (1) and (2), \( \Gamma_{L/R} \) are the tunnel couplings between the QD level and the source/drain reservoir and \( e \) is the elemental charge. Further,

\[
f_{LR} = \frac{1}{e^{\frac{-\Delta \epsilon + V_{SD}/2}{k_B T_{LR}}} + 1}
\]
is the Fermi–Dirac distribution of the left/right lead at the QD level position ($\mu_{QD}$) relative to the electrochemical potential of the leads ($\mu_{SD}$): $\delta E = \mu_{SD} - \mu_{QD}$ [20]. The ability to implement a symmetric device bias is included in (3) and $k_B$ denotes the Boltzmann constant. We note that (1) and (2) are capable of describing both, bias driven currents $I_{fb}$ and thermocurrents $I_{th}$ [20, 38].

The experimentally detected thermocurrent along the red dashed cutline in figure 2(a) for a heating bias $dV_R = 46$ mV is presented in figure 2(c). Each charge state transition gives raise to a characteristic TE signal in a range of several $k_B T$ around $\mu_{SD}$ where $[f_L - f_R] \gg 0$. Positive current peaks corresponds to a net electron flow from the hot to the cold reservoir where the QD resonance is situated above $\mu_{SD}$ (illustrated in figure 2(d)). Negative current peaks correspond to electrons traveling from the cold to the hot side when the QD level is tuned energetically below $\mu_{SD}$ (see figure 2(e)).

For the thermocurrent signal around $\delta E = 0$ the amplitude of the negative current peak exceeds that of the positive current peak. This suggests that current is limited in a configuration where $\mu_{QD} > \mu_{SD}$ and $f_{LR} < 0.5$. Consequently, the resonance is mostly unoccupied and we identify the tunneling process into the QD as spin-selective, thus thermocurrent-limiting, and find an effective $1 \rightarrow 2$ charge state transition, illustrated in figure 2(d). Conversely, for the TE signal around $\delta E \approx 5$ meV transport through a mostly occupied QD level ($\mu_{QD} < \mu_{SD}, f_{LR} > 0.5$) yields a lower thermocurrent amplitude (see figure 2(e)). Here tunneling out of the resonance is the limiting factor and we identify an effective $0 \rightarrow 1$ QD charge state transition. We therefore use (2) and (1) to first fit Coulomb peaks corresponding to the first and second signal in figure 2(c) and obtain the tunnel couplings in table 1.

With knowledge of the tunnel couplings, we fit the data in figure 2(c) for the reservoir temperatures with a combination of (2) and (1), where an offset correcting factor is added to $f_{LR}$ in (1) to account for the energy gap between the two QD resonances. The fit (solid red line) is in good agreement with the experimental data and yields $T_L = 0.75 \pm 0.01$ K and $T_R = 1.10 \pm 0.01$ K.

In figures 3(a)–(d) we present thermocurrent measurements as discussed in figure 2(c) as a function of the heater bias $dV_H$ for different combinations of heater and QD locations: QDL heated from g2 (a) and g7 (b) and QDR heated from g2 (c) and g7 (d). The results clearly highlight how the TE signals grow wider for increased heater bias and revert polarity due to the temperature gradient reversal when heating is applied on different sides of the device. We further find traces of excited state contributions to the thermocurrent in (b) and (d), which will be addressed briefly in section 5.

To obtain a detailed picture of the heater effect on the device in a QD geometry, we repeat the thermometry fits on figures 3(a)–(d) and the results for the absolute temperature difference $\Delta T$ and the average temperature $\bar{T}$ as a function of $dV_H$ are presented in figures 3(e) and (f), respectively. Due to the non-negligible effect of excited states already at low heating bias in figure 3(d) the fit is limited to the TE signal around $\delta E = 0$. We note that the quality of the fit results varies with the heating bias. For low heating the TE signal only consists of very few data points and is affected heavily by the offset bias drift. In contrast, for high heating bias excited states begin to contribute to the TE signal lineshape, which is not covered by the fit. Thus, the best agreement between the fit and data is found in a range $dV_H = [10 \ldots 80]$ mV.

Interestingly, the fit reveals comparable $\bar{T}$ across all probed heater and QD combinations. In contrast, $\Delta T$ coincides only when either QD is heated from the opposite nanowire end and QDL heated from the left (g1) side results in clearly suppressed $\Delta T$. For QDL heated from the right $\Delta T$ initially increases steeply before a decrease in slope at $dV_R \approx 40$ mV occurs.

To understand the temperature dependence on the heating location, consideration of the heat transfer mediating mechanisms across the nanowire is relevant: first, hot electrons diffuse through the nanowire, leading to an electronic heat flow contribution, dependent on the electron conductivity. Second, hot phonons diffuse through the nanowire and via electron–phonon coupling increase the electron temperature along their path. This phononic heat flow contribution is heavily dependent on the coupling between the phonon and electron bath in the system [39] and the phonon mean free path (PMFP).

Table 1. Tunnel couplings for the first ($1 \rightarrow 2$ charge state transition) and second ($0 \rightarrow 1$ charge state transition) resonance of QDL and QDR extracted from fits to Coulomb peaks.

|                  | Left QD  | Right QD |
|------------------|----------|----------|
| $\Gamma_{L,R}^{\pm}$ (GHz) | $0.038 \pm 0.005$ | $0.110 \pm 0.005$ |
| $\Gamma_{L,R}^{\mp}$ (GHz) | $0.076 \pm 0.005$ | $0.036 \pm 0.005$ |
| $\Gamma_{L,R}^{\pm}$ (GHz) | $0.054 \pm 0.005$ | $0.013 \pm 0.005$ |
| $\Gamma_{L,R}^{\mp}$ (GHz) | $0.367 \pm 0.005$ | $0.036 \pm 0.005$ |
In the barrier-free nanowire configuration in section 2 the electronic thermal resistance is assumed very low as a direct consequence of the high device conductance, leading to an almost uniform nanowire temperature profile [39]. This is changed by the introduction of a QD to the system. The QD drastically decreases the conductance and suppresses electronic heat transfer away from the charge degeneracy points [40, 41], while the phononic contribution is expected to remain unaffected by the QD [7, 39]. Because the heating power in our symmetric bottom-heater architecture only depends on the magnitude of $dV_H$ rather than the heater location or nanowire configuration, $\tilde{T}$ is found to coincide for all tested QD and heater combinations. In contrast, $\Delta T$, which for the TE effect to occur must be present between the nanowire lead segments surrounding the QD, now becomes strongly dependent on the ratio of the electronic to the phononic heat transfer contributions.

The decreased $\Delta T$ for heating in close vicinity to the QD as opposed to heating at a larger distance on the opposite device end indicates that (i) phononic heat transfer is an important contribution to the overall heat flow across the nanowire in the presence of a QD and (ii) the coupling strength of the phonon to the electron thermal reservoir and PMFP now strongly influence the magnitude of the temperature difference $\Delta T$. Consequently, the lower $\Delta T$ detected for QDL when heated on the left side (and also QDR for high $dV_R$) compared to heating from the right (left) side is attributed to an increased phonon mediated heat flow across the QD in close vicinity to the heater electrode.

4. Thermocurrents in double quantum dots

Qualitative insight on the phonon energies and PMFP in the device can be obtained by studying a configuration in which heat transfer from the hot phonon bath to the electron reservoirs is directly converted to a thermocurrent. This is achieved by the formation of a DQD, combining the left and right QD. In DQD structures, thermocurrents of two different origins are experimentally reported in literature: the TE effect [28, 42] and PAT [28, 43–46]. In recent work, we demonstrated that a weakly coupled DQD is ideal for the detection of PAT, while a strong interdot coupling regime favors observation of the TE effect [28].

Consequently, in order to identify both possible thermocurrent effects reliably, we tune the DQD to an intermediate interdot coupling regime where not only characteristically clear finite bias triangles but also avoided-crossing behavior near the triple points (TP) are observed [10]. The resulting charge stability diagram at $V_{SD} = 100 \mu V$ is shown in figure 4(a). The device configuration, where $g_2$, $g_4$ and $g_6$ ($V_2 = -0.14$ V, $V_4 = 0.04$ V, $V_6 = -0.23$ V) are used to induce barriers, is schematically illustrated in figure 4(b). From the charge stability diagram (inset figure 4(a): $V_{SD} = 2$ mV) we extract lever arms $\alpha_{DQD} = 0.47 \pm 0.02$ eV V$^{-1}$ and $\alpha_{DQD} = 0.43 \pm 0.02$ eV V$^{-1}$. The characteristic axis $\epsilon = \mu_{SD} - E_{L,R}$ along which the ground-states of the left ($E_L$) and right ($E_R$) QD are aligned and shifted together in energy is indicated by an orange arrow and the level detuning axis $\Delta = E_L - E_R$ by a green arrow.
scattering with the assumption of an exponential decay of the phonon energy increase at lower temperatures as a result of a reduction in electron–phonon and phonon–phonon scattering. We also observe a weak TE effect along the level detuning axis South to the heater electrode discussed in section 3.

In a regime where PAT occurs, the DQD essentially acts as a sensitive, energy resolved detector for hot phonons—a concept also exploited for the detection of noise and photons. The total extent of the PAT signal along \( \Delta \) is a measure for double the maximum energy that can be supplied by phonons for electrons to overcome \( \Delta \), \( 2E_{\text{ph}} \). To estimate \( E_{\text{ph}} \), we locate where along \( \Delta \) the positive and negative current signal drops below 1\% of its maximum amplitude (orange dashed lines in figure 4(c)). At \( \Delta V_{\text{M}} = 5 \text{ mV} \) this analysis yields a lower bound for \( E_{\text{ph}} = 0.52 \pm 0.08 \text{ meV} \).

Next, we test the impact of the heater location on the thermocurrent across the DQD in an expanded plunger gate range for which the charge stability diagram at \( V_{\text{SD}} = 100 \mu \text{V} \) is shown in figure 5(a). Figures 5(b)–(d) present the corresponding thermocurrents at \( \Delta V_{\text{M}} = 40 \text{ mV} \) (b), \( \Delta V_{\text{L}} = 40 \text{ mV} \) (c) and \( \Delta V_{\text{R}} = 40 \text{ mV} \) (d). For each set of TPs, signals are conceptually comparable to figure 4(c). Between figures 5(b) and (c)/(d), however, a reduction of the PAT signal width along \( \Delta \) is observed.

To quantify the phonon energies in the nanowire at the position of the DQD and dependent on the heating location, we extract \( E_{\text{ph}} \). The results with heat applied on g1, g4 or g7 as a function of the heating bias are shown in figure 5(e). For heating on g4 (black circles), where most data points are available, we find a clear scaling of \( E_{\text{ph}} \) with \( \Delta V_{\text{M}} \).

A direct comparison at \( \Delta V_{\text{M}} = 40 \text{ mV} \) yields an average reduction of \( E_{\text{ph}} \) by a factor of 0.64 for heating on g1/7 as opposed to applying heat to g4. Further, to obtain similar phonon energies to heating with \( \Delta V_{\text{M}} = 40 \text{ mV} \), a heater bias of \( \Delta V_{\text{R}} = 100 \text{ mV} \) is required. We explain the detected reduction in \( E_{\text{ph}} \) for an increased distance to the heat source \( d \) with damping of the phonons by scattering events [50]. In InAs nanowires at room temperature, PMFPs of \( l_{\text{ph}} = 250 \pm 40 \text{ nm} \) have been reported [51] and are expected to increase at lower temperatures as a result of a reduction in electron–phonon and phonon–phonon scattering [50]. With the assumption of an exponential decay of the phonon energy \( E_{\text{ph}} \propto e^{-d/l_{\text{ph}}} \) and a heater center-to-center distance of \( d = 300 \text{ nm} \) between g1/7 and g4, we also estimate the PMFP in the nanowire \( l_{\text{ph}} \) of several hundred nanometers. The estimated PMFP, which is of the same order of magnitude as the bottom-gate spacing, provides additional evidence of an increase in the phononic heat flow across single QDs formed close to the heater electrode discussed in section 3.

Figure 4(c) shows the thermocurrent across the DQD as a function of the plunger gate biases \( V_3 \) and \( V_5 \) at \( \Delta V_{\text{M}} = 5 \text{ mV} \) in a comparable range to (a). Thermocurrent signals are observed around each TP and we identify two separate transport contributions: along the level detuning axis \( \Delta \) directional electron transport is achieved by lifting electrons from an energetically lower, occupied to a higher, unoccupied level on the other QD via phonon absorption. This PAT process requires the temperature of the phonon bath \( T_{\text{ph}} > T_{\text{LR}} \) to exceed that of the electronic system [47] and is schematically illustrated in figure 4(d). In addition, we also observe a weak TE effect along \( \epsilon \), where the DQD effectively behaves like a single QD as sketched in figure 4(e). The polarity of the TE effect indicates \( T_{\text{L}} > T_{\text{R}} \) which is in line with the observation in section 2 for heating a barrier-free nanowire configuration on g4. A detailed discussion and disentangling of PAT and the TE effect contribution in DQDs is found in [28].
Figure 5. Impact of heater location and phonon energies. (a) Charge stability diagram at $V_{SD}=100\,\mu V$. (b)–(d) Thermocurrents measured at (b) $dV_M=40\,mV$, (c) $dV_L=40\,mV$ and (d) $dV_R=40\,mV$. The currents are plotted logarithmically with a linear scale in the $\pm0.1\,pA$ range. Inset: orientation of the characteristic axis $\epsilon$ and $\Delta$. (e) Lower bound for the maximum phonon energy $E_{\text{ph}}$ as a function of $dV_H$, $H\in\{L, M, R\}$. (f) TE thermocurrent linecut along the axis $\epsilon$ extracted from (c) and (d) for heating on the left (red curve) and right (blue curve) heater. The cutlines are labeled in (c) and (d) and data points along the cutline are extracted using bilinear interpolation at the original data point spacing.

Figure 6. Resonances in DQD thermocurrents. (a) Charge stability diagram at $V_{SD}=2\,mV$. (b) Charge stability diagram at $V_{SD}=-2\,mV$. (c) Thermocurrent measurement at $dV_R=40\,mV$, plotted logarithmically with a linear scale in the $\pm0.1\,pA$ range. The chosen colourmap is saturated at $\pm1.5\,pA$ for better visibility of relevant features. Selected resonances in (a) and (b) are labeled by dashed lines. Resonances corresponding to the ones indicated in (a) and (b) are indicated by colour-coded arrows in (c). Resonances attributed to the TE effect are further labeled by a black arrow.

In addition to insights on the PMFP, a comparison of figures 5(b)–(d) further reveals that the magnitude and polarity of the TE effect along $\epsilon$ depends strongly on the choice of the heater location and is more pronounced for side- in contrast to center heating. To illustrate the TE effect more clearly, we extract cutlines along $\epsilon$ for heating on $g_1$ (red dashed line in figure 5(c)) and $g_7$ (blue dashed line in figure 5(d)). The thermocurrents along these cutlines are shown in figure 5(f) and demonstrate the reversed polarity of the TE signals forming around each TP. From the polarity of $I_{\text{th}}$, we find as expected $T_L>T_R$ for heating on the left and $T_R>T_L$ for heating on the right side of the DQD as illustrated in the insets of figure 5(f).

In line with the discussion in [28] we further observe distinct resonances in the thermocurrent signals in figures 5(c) and (d). A comparison of charge stability diagrams measured at $V_{SD}=2\,mV$ (figure 6(a)) and $V_{SD}=-2\,mV$ (figure 6(b)) to a corresponding thermocurrent measurement at $dV_R=40\,mV$ (figure 6(c)) yields energetically matching resonances. Resonances attributed to transport through the same QD levels are labeled with matching colors across figures 6(a), (b) (dashed lines) and (c) (colored arrows).

The observed thermocurrent resonances can, in line with the detailed description given in [28], be attributed to two separate effects: (i) PAT from a populated ground- to an unpopulated and aligned ground- and excited-state pair in the two QDs or (ii) the TE through aligned (excited-) states in both QDs. While in [28] the observed resonances in the thermocurrent are attributed purely to PAT, we find a polarity reversal of the current upon following certain resonances (labeled by black arrows in figure 6(c)) along $\epsilon$. Because a pure PAT process leads to no current polarity reversal along $\epsilon$ the observed current modulation...
on the resonance is characteristic for a TE contribution to the thermocurrent on the resonance. The remaining resonances, not indicated with black arrows in figure 6(c), do not exhibit a thermocurrent polarity reversal and are thus the result of a PAT process via excited states. Further details of the origin of thermocurrent resonances in DQDs is given in [28]. Finally, we note that for heating on g4, the thermocurrent resonances are suppressed as a result of the increased background PAT signal magnitude due to the higher $T_{th}$ and the absence of a clear TE effect for near symmetric heating. Consequently, resonances in the thermocurrent appear more distinct when heat is supplied from g1 or g7.

5. Conclusion and outlook

We have characterized an InAs nanowire situated on an array of seven bottom-gates, where selected gates are used to locally apply heat to the device. This device architecture not only enables the formation of various barrier and multi-barrier structures, with full control over relevant tunnel couplings, but also allows local heating with a near perfect symmetry with respect to the electrostatically defined barrier configurations. The low-temperature experiments presented here verify the device concept by studying thermocurrents in a plain nanowire configuration, electrostatically defined QDs and a DQD. We find the device to produce high quality bias and thermocurrent data and confirm symmetric heating effects when heating with different gates.

The transition from a barrier-free nanowire to a QD configuration is expected to drastically affect heat flow through the nanowire as a result of the suppressed electronic heat flow contribution [39, 41]. We use thermocurrent measurements on QDs situated on different sides of the nanowire to probe the local temperature on the either side of the barriers. By selection of suitable charge transitions on each QD, similar to epitaxially defined QDs [18], simple thermometry is accessible for moderate heating without excited state effects being present. The results indicate the importance of a heater-to-QD distance dependent phononic heat-flow in the InAs nanowire. By using a DQD as an energy selective phonon detector, we find that our heating technique elevates the temperature of the phonon-bath beyond the electronic temperature of the device. Further, the DQD PAT measurements confirm a phonon energy loss for an increased DQD-center distance to the heater, which indicates a PMFP of the order of magnitude of the gate-electrode spacing.

Based on the proof-of-principle work presented in this paper, we suggest in the following a selection of research directions and future experiments for which we believe our combined bottom-gate and heater architecture to be ideally suited.

**PAT in single QDs:** In figure 3(d) for the charge state transition at $\delta E \approx 5$ meV we observe additional effects to the ground-state TE effect for QD$_3$ heated from the right (also QD$_1$, heated from the left) as opposed to heating from a larger distance on the leftmost (rightmost) gate. Because $\Delta T$ and $\tilde{T}$ are comparable across both measurements, this indicates an origin other than an excited state contribution to the TE effect. The apparent heater-distance dependence suggests a PAT-based effect. In QDs, microwave photon absorption in the contacts reportedly leads to similar signals [52, 53] but detection requires either charge sensing [54], a bias $V_{sd}$ [55] or an asymmetric coupling of the microwave-field to the source- and drain reservoirs [56]. As a result of the short PMFP in our nanowire, the phonon-bath could be coupled differently to the source and drain electron reservoirs, but the observed effect warrants further investigation.

**Heat flow characterization:** The ability to (i) use QDs for electron thermometry, (ii) DQDs for phonon detection, (iii) change the location of the QD and DQDs with respect to the heater position in controlled steps and (iv) control all relevant tunnel couplings sets the stage to study heat flow characteristics and the PMFP in nanowires. This not only allows independent characterization of the electronic and phononic heat transfer across the nanowire but also serves as a test bed for deviations from the Wiedmann–Franz law, which are expected in QD devices and vary with the coupling to the leads [40, 57–60].

**Three-terminal thermal energy harvesting:** The PAT process in DQDs essentially converts a heat flow from a hot phonon-bath to the electron-bath to electrical power and thus acts as a three-terminal energy harvester [28, 61, 62]. Such systems have gained interest in recent years as they allow access to a regime where fluctuations are highly relevant and thermodynamic uncertainty relations are theoretically predicted to result in trade-offs between power, power fluctuations and the efficiency [63, 64]. Further, a DQD coupled to a phonon-bath has a predicted functionality as phonon TE transistor and rectifier [65]. Our device architecture offers ideal conditions to study the properties of a DQD thermal energy harvester.

**P–n hybrid devices:** Our gate architecture allows (i) fully independent gating of separate nanowire sections and (ii) symmetric heating in the nanowire center. In combination with a small bandgap semiconductor nanowire, such as InSb [66], where through moderate gating either p- or n-type behavior
can be induced, a single nanowire p–n thermocouple can be realized. This is possible by heating in the center of two nanowire segments tuned to a p- and n-regime, respectively. Taking this concept further, a serial DQD consisting of a p- and n-type QD can be phonon coupled and via PAT give insight into electron–hole interactions where traditional current spectroscopy is blocked.

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Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

ORCID iDs

Sven Dorsch  https://orcid.org/0000-0002-4314-945X
Adam Burke  https://orcid.org/0000-0001-9345-2812

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