Integrated impedance bridge for absolute capacitance measurements at cryogenic temperatures and finite magnetic fields

G. Verbiest, H. Janssen, D. Xu, X. Ge, M. Goldsche, J. Sonntag, T. Khodkov, L. Banszerus, N. von den Driesch, D. Buca, Watanabe, T. Taniguchi, and C. Stampfer

1) JARA-FIT and 2nd Institute of Physics, RWTH Aachen University, 52056 Aachen, Germany, EU
2) Current address: 3mE, Delft University of Technology, 2628 CD Delft, The Netherlands, EU
3) QuTech and Kavli Institute of Nanoscience, Delft University of Technology, 2600 GA Delft, The Netherlands, EU.
4) Peter Grünberg Institute (PGI-8/9), Forschungszentrum Jülich, 52425 Jülich, Germany, EU
5) National Institute for Materials Science, Tsukuba, Ibaraki 305-0047, Japan

We developed an impedance bridge that operates at cryogenic temperatures and in perpendicular magnetic fields up to at least 12 T. This is achieved by mounting a GaAs HEMT amplifier perpendicular to a printed circuit board containing the device under test and thereby parallel to the magnetic field. The best resolution is obtained when operating the HEMT amplifier at the highest gain. We obtained a resolution in the absolute capacitance of 6.4 aF/√Hz at 77 K on a comb-drive actuator, while maintaining a small excitation amplitude of 15 kBT/e. We show the magnetic field functionality of our impedance bridge by measuring the quantum Hall plateaus of a top-gated hBN/graphene/hBN heterostructure at 60 mK with a probe signal of 12.8 kBT/e. The measured amplitude and phase of the output signal allows for the separation of the total impedance into an absolute capacitance and an effective resistance.

I. INTRODUCTION

Electronic and electromechanical devices are characterized by an impedance that defines their functionality. Thus, an accurate measurement system for impedances is thus of crucial importance to develop, characterize, and optimize electronic and electromechanical devices. Impedances are commonly measured with bridge circuits or LCR-meters. The ongoing miniaturization of electronic and electromechanical devices push these measurement techniques to the limit. For example, the density of available electronic states in nanostructures becomes finite which results in a so-called quantum capacitance or the displacement of electromechanical devices enter the nanoscale. Both these examples result typically in capacitance changes of only a few aF. Standard measurement techniques cannot resolve these changes due to parasitic impedances arising from lengthy cables connecting the device under test (DUT) and the measurement system. Direct measurements of the density of states via the quantum capacitance have been successful for among others, graphene and carbon nanotube devices as well as GaAs-based devices containing a two-dimensional (2D) electron gas. In such systems with a low density of states the total capacitance needs to be expressed by the quantum capacitance \( C_q \) in series to the geometric capacitance \( C_g \) leading to a total capacitance \( C_{\text{tot}} = C_q C_g / (C_q + C_g) \), which is also strongly depending on the density of states. Measurements of this quantity were performed with a bridge circuit, a LCR meter, or even a scanning tunneling microscope. The latter provides local information whereas the former characterizes the entire device. In order to fully resolve fine features in their electronic bandstructure such as van Hove singularities in carbon nanotubes, a probe signal on the order of the characteristic thermal energy \( k_B T/e \) is required. However, bridge circuits and LCR meters usually include some lengthy cables which give rise to a parasitic capacitance in the order of hundreds of picoFarads. This large parasitic capacitance results in a huge attenuation of the probe signal which, in combination with the required \( k_B T/e \) excitation, pushes attofarad capacitance changes below the resolution limit. To reduce the effect of the parasitic capacitance of the cables, Hazeghi et al. used a high-electron mobility transistor (HEMT) as an impedance-matching amplifier in an integrated capacitance bridge. A resolution of 60 aF/√Hz at 300 K and 21 aF/√Hz at 4.2 K was achieved on a top-gated graphene device with probe signals on the order of \( k_B T/e \). However, a problem arises if the density of states approaches zero. As \( C_q \) approaches zero, also the conductance approaches zero due to the absence of charge carriers. Depending on the frequency of the probe signal, the measured signal becomes a function of both and thus depends on the total impedance.

In this work, we show an integrated impedance bridge to determine the absolute capacitance and the effective resistance. The integrated impedance bridge is placed on a printed circuit board (PCB) that allows for magnetic field dependent measurements. We achieve a resolution of 6.4 aF/√Hz at a temperature of 77 K. To show the magnetic field applicability of our circuit, we measure the quantum Hall plateaus emerging in a top-gated hBN/graphene/hBN heterostructure in magnetic fields up to 12 T at 60 mK. By recording the amplitude and the phase of the output signal, we are able to separate the total admittance into a capacitance and a resistance.
A bridge circuit (see Fig. 1(a)) consists of a reference resistor and an impedance-matching amplifier. The HEMT in our bridge circuit is a packaged FHX35LG transistor with a gate capacitance of approximately 0.5 pF that is part of a small remaining parasitic capacitance $C_{\text{par}}$. A gate bias $V_{\text{ref}}$ of 1 V fully depletes the 2D electron gas in the GaAs-based HEMT.

The reference resistor $R_{\text{ref}}$ is used to balance the signal across the unknown impedance $Z_{\text{DUT}} = Y_{\text{DUT}}^{-1}$, where $Y_{\text{DUT}}$ is the corresponding admittance of the device under test (DUT). As the HEMT gate (G) is biased through $R_{\text{ref}}$, $R_{\text{ref}}$ should be much larger than the HEMT DC gate resistance across all temperatures. In addition, $R_{\text{ref}}$ forms together with $C_{\text{par}}$ and the capacitive contribution of $Z_{\text{DUT}}$, a low-pass filter. We choose $R_{\text{ref}}$ equal to the impedance of the expected $Z_{\text{DUT}}$ parallel to a parasitic capacitance $C_{\text{par}}$ at the measurement frequency to prevent additional shunting of the signal across $Z_{\text{DUT}}$. To satisfy these constraints and to maximize the bandwidth, we use a reference resistance $R_{\text{ref}}$ of 1 MΩ with a low temperature coefficient (SMD type thick film resistor).

The output circuit (see Fig. 1(b)) consists of a load resistor and the drain (D) to source (S) resistance of the HEMT. $R_{\text{load}}$ is used to bias the HEMT drain with the voltage $V_{\text{dd}}$. To ensure stable operation, $R_{\text{load}}$ must be larger than the resistance of the cables. Therefore, we choose a $R_{\text{load}} = 1$ kΩ. The maximum amplification is expected when the drain-source resistance of the HEMT is roughly equal to $R_{\text{load}}$. We always place $R_{\text{load}}$ at room temperature to minimize the heat load of the output circuit. While measuring in a dilution refrigerator (a Triton 200 system), the temperature, as measured with a built-in calibrated RuO$_2$ sensor, increased from 15 mK to 50 mK when biasing the HEMT drain with $V_{\text{dd}} = 0.55$ V.

For successful operation of the circuit in a perpendicular magnetic field, we place the HEMT on a small PCB that is mounted perpendicular to the PCB containing $R_{\text{ref}}$ and $Z_{\text{DUT}}$ (see Fig. 1(b)). We characterized both $R_{\text{ref}}$ and the HEMT in a Triton 200 system at mK temperatures for different applied magnetic fields. $R_{\text{ref}}$ is approximately 0.98 MΩ at room temperature and 1.03 MΩ at 30 mK. Both values are within the 3% tolerance given by the manufacturer. As Fig. 2a shows, $R_{\text{ref}}$ only changes by 0.1% when applying a magnetic field of 12 T perpendicular to the PCB containing $R_{\text{ref}}$. Similarly, the operation of the HEMT remains unaffected when a magnetic field is applied parallel to the drain-source channel of the HEMT (see Figs. 3 and 4). We conclude that the resulting Lorentz forces acting on the 2D electron gas have no effect and thus that the integrated impedance bridge remains fully functional.

In operation, two AC signals at the same frequency are used, of which one is sent through a reference resistance $R_{\text{ref}}$ ($v_{\text{ref}}$) and one through the DUT ($v_{\text{DUT}}$). The amplitude and phase of these signals are set such that they interfere destructively at the so-called bridge point at the gate of the HEMT. The signal $v_b$ at the bridge point is an average of the applied AC signals $v_{\text{ref}}$ and $v_{\text{DUT}}$,

$$v_b = \frac{Y_{\text{DUT}} \cdot v_{\text{DUT}} + Y_{\text{ref}} \cdot v_{\text{ref}}}{Y_{\text{ref}} + Y_{\text{DUT}} + Y_{\text{par}}},$$  

where $Y_{\text{ref}}$, $Y_{\text{DUT}}$, and $Y_{\text{par}}$ are the admittances of $R_{\text{ref}}$, $Z_{\text{DUT}}$, and $C_{\text{par}}$, respectively. When balanced ($v_b = 0$ V), the amplitude and phase of $Y_{\text{DUT}}$ are given by

$$Y_{\text{DUT}} = \frac{Y_{\text{ref}} \cdot v_{\text{ref}}}{v_{\text{DUT}}}. \quad (2)$$

As $Y_{\text{DUT}}$ is the only quantity that is tunable with the DC voltage $V_{\text{DUT}}$, we need to characterize the other admittances in the circuit only once. The signal $v_b$ is amplified $A_{\text{HEMT}}$ times by the HEMT into the output voltage $v_{\text{out}} = A_{\text{HEMT}} \cdot v_b$, which is measured with a lock-in amplifier. The measured amplitude and phase of the output voltage $v_{\text{out}}$ is used in Eq. (1) to compute the unknown $Y_{\text{DUT}}$. The sensitivity $S$ of the circuit to a change in $Y_{\text{DUT}}$ is given by the derivative of Eq. (1) with respect to $Y_{\text{DUT}}$

$$S = \frac{Y_{\text{ref}} \cdot (v_{\text{DUT}} - v_{\text{ref}}) + Y_{\text{par}} \cdot v_{\text{DUT}}} {(Y_{\text{ref}} + Y_{\text{DUT}} + Y_{\text{par}})^2}. \quad (3)$$
If \( Y_{\text{DUT}} \) is a pure capacitor, the minimal detectable change \( \delta C_{\text{DUT}} \) in \( C_{\text{DUT}} \) is therefore given by

\[
\delta C_{\text{DUT}} = \frac{\nu_{\text{noise}}}{|A_{\text{HEMT}} \cdot \omega \cdot S|},
\]

where \( \nu_{\text{noise}} \) is the spectral density of the voltage noise arriving at the input stage of the lock-in amplifier and \( \omega \) is 2\( \pi \) times the measurement frequency.

For the optimization of the resolution to determine \( Y_{\text{DUT}} \), we used a voltage controlled capacitor (SVC704\textsuperscript{24}). All measurements in this work were performed at 100 kHz. The required bias potentials were applied with Yokogawa 7651 DC sources. The output of the bridge circuit was measured with a Zurich Instruments lock-in amplifier (model UHF). As we did not observe any phase shifts in \( \nu_{\text{out}} \), we model \( Y_{\text{DUT}} \) with a capacitance \( C_{\text{DUT}} \). We balanced the bridge at four different \( V_{\text{DUT}} \) and extracted \( C_{\text{DUT}} \) according to Eq. (2) and \( C_{\text{par}} \) from the \( \nu_{\text{ref}} \) dependence of Eq. (1). The data points in Fig. [3] show that \( C_{\text{par}} \) is four times bigger than the gate capacitance of the HEMT, which indicates a significant contribution coming from the PCB itself. We also swept \( V_{\text{DUT}} \) for five different pairs of \( \nu_{\text{ref}} \) and \( \nu_{\text{DUT}} \) while recording \( \nu_{\text{out}} \) and translated this into \( C_{\text{DUT}} \) using Eq. (1). As depicted in Fig. [3](c), the extracted capacitances from all the different measurements are in excellent agreement with one another. The absolute values are also in good agreement with the datasheet of the voltage controlled capacitor.\textsuperscript{24} Now confident that our bridge circuit gives reproducible data, we balanced the circuit at \( V_{\text{DUT}} = 10 \) V and fixed \( \nu_{\text{ref}} \) and \( \nu_{\text{DUT}} \). Then, we measured \( \nu_{\text{out}} \) as a function of \( V_{\text{DUT}} \) for different HEMT amplifications \( A_{\text{HEMT}} \). At each \( V_{\text{DUT}} \), we recorded 100 points with a rate of 1 point/s to estimate the noise in \( \nu_{\text{out}} \), and thus in \( C_{\text{DUT}} \). We define the resolution as the root-mean-square value of the noise in \( C_{\text{DUT}} \), in orders of magnitude when increasing \( V_{\text{DUT}} \) from 0 V to 10 V (see Fig. 3). As Eq. (3) shows, the sensitivity \( S \) scales with \( C_{\text{DUT}}^2 \), if \( |Y_{\text{DUT}}| \) is (much) larger than \( |Y_{\text{ref}} + Y_{\text{par}}| \). Considering this scaling relation and the measured \( C_{\text{DUT}} \) values depicted in Fig. [3], the observed improvement in resolution is in agreement with the decrease by one order of magnitude in \( C_{\text{DUT}} \).

To explore the limits of the achievable resolution with the bridge circuit, we performed measurements on a device with a negligible \( |Y_{\text{DUT}}| \) compared to \( |Y_{\text{ref}} + Y_{\text{par}}| \) such that the sensitivity \( S \) becomes independent from \( Y_{\text{DUT}} \). For these measurements, we choose a silicon-based micro-machined comb-drive actuator which we fabricate following the process described in Refs. \textsuperscript{5} and \textsuperscript{6}. In short, the substrate consists from bottom to top of a 500 \( \mu \)m thick undoped Si layer, a 1 \( \mu \)m thick SiO\textsubscript{2} layer, and a 1.2 \( \mu \)m chemical vapor deposited crystalline, highly p-doped silicon layer. The doping of the top layer is \( >10^{19} \) cm\textsuperscript{3}, making our devices low temperature compatible. Using standard electron beam lithography techniques and reactive ion etching with \( \text{C}_4\text{F}_8 \) and \( \text{SF}_6 \), we pattern the comb-drive actuators as shown in Fig. [3]. The actuator is suspended by etching the SiO\textsubscript{2} underneath the highly p-doped silicon layer away with 10% HF acid solution. Finally, a critical-point drying step is used to prevent the comb-drive actuator from collapsing due to capillary forces. The comb-drive actuator consists of a suspended body that is held by four springs and a part that is fixed to the substrate. The interdigitated fingers of the suspended body and the fixed part gives rise to an effective parallel plate capacitance of approximately 13 fF. As the fingers are asymmetrically placed (see Fig. [4]), the potential \( V_{\text{DUT}} \) applied to the fixed part gives rise to an electrostatic force \( F \sim V_{\text{DUT}}^2 \), which results in a displacement of the suspended body and thus into a change of the capacitance. As the undoped silicon
substrate becomes completely insulating around 150 K, we use the impedance bridge at 77 K to measure this capacitance. This allows us to exclude any effects coming from the undoped silicon. The output of the bridge circuit was measured with a Stanford Research lock-in amplifier (model SR830). The measurement was performed with a small \(v_{\text{in}}\) of 88.9 \(\mu V\) or 15 \(k_{\text{B}}T/e\) (frequency of 100 kHz). We did not observe any phase shifts in \(v_{\text{out}}\) and thus model \(V_{\text{DUT}}\) with only a capacitance \(C_{\text{DUT}}\). As Fig. 3 shows, the capacitance of this device is 73 fF and increases to 79 fF at \(V_{\text{DUT}} = 5\) V. We determined \(C_{\text{par}}\) to be 6.5 pF using the same method as for the voltage controlled capacitance discussed above. The capacitance is a few tens of fF higher than the one from the parallel plate approximation for the interdigitated fingers due to additional capacitances coming from stray fields, bond wires, and other parts of the comb-drive actuator. The quadratic dependence of \(C_{\text{DUT}}\) on \(V_{\text{DUT}}\), albeit offset such that the minimum \(C_{\text{DUT}}\) is at \(V_{\text{DUT}} \approx -5\) V, is in agreement with the electrostatic force between the interdigitated fingers. The offset is due to residual charges from the fabrication process. The resolution (see Fig. 4d) does, as expected, not depend on \(C_{\text{DUT}}\), which is illustrated by the constant red line below \(V_{\text{DUT}} = 3.3\) V. The red line illustrates a resolution of 6.4 aF/√Hz, which shows the feasibility of using the bridge circuit for measuring the capacitance of such comb-drive actuators with sub-nm resolution.

III. EXPERIMENTAL SETUP AND MEASUREMENTS

To show the applicability of the impedance bridge at low temperatures in a high magnetic field, we fabricated a hBN/graphene/hBN heterostructure with a gate on top. We grow the graphene using chemical vapor deposition on a copper foil and then use a dry transfer process to fabricate a hBN/graphene/hBN heterostructure on an undoped Si/SiO\(_2\) substrate. All required hBN sheets are obtained via mechanical exfoliation. We structure the heterostructures afterwards using electron beam lithography and reactive ion etching to obtain a well defined geometry of 20 × 20 \(\mu m^2\). This is subsequently followed by electron beam lithography and Cr/Al evaporation to obtain Ohmic contacts to the graphene sheet. Then we
use the dry transfer process\textsuperscript{29} to cover the heterostructure and the Ohmic contacts by an additional hBN sheet. Finally, we use electron beam lithography and Cr/Ag evaporation to fabricate a gate on top of the heterostructure. The area of the top gate is $15 \times 15 \mu m^2$ and the hBN layers between the graphene and the top gate are roughly 31 nm thick, which results in a parallel plate capacitance of 0.25 pF when using a relative permittivity of 3.9 for the hBN. An atomic force microscopy image of the final device is shown in Fig. 5a. Finally, an Ohmic contact of the device was wirebonded to the impedance bridge. For completeness, we note that the other two Ohmic contacts were kept floating during the measurement and that the four top gates covering the edge of the graphene were grounded.

Measurements were carried out in a Triton 200 cryostat from Oxford Instruments that is equipped with a superconducting magnet of up to $B = 12$ T. The HEMT drain voltage $V_{dd}$ was biased with 0.55 V to avoid instabilities in its drain-source channel. The gate of the HEMT was biased with -0.29 V for operation at its highest amplification (see Fig. 2a). Due to current flowing through the drain-source channel, the temperature in the cryostat increased from 15 mK to 50 mK. The impedance bridge is then used to measure the complex admittance from the top gate through the graphene sheet to the gate of the HEMT. We balance the bridge for a chosen $V_{DUT}$ on the order of $k_B T/e$ by adjusting the amplitude and phase of $v_{ref}$. Note that $v_{ref}$ is smaller than $V_{DUT}$ for the measurements here. From the balance point, we extract the complex admittance $Y_{DUT}$ using Eq. 2. Then, we sweep the bias $V_{DUT}$ of the top gate as a function of an externally applied magnetic field while recording the amplitude and the phase of the output $v_{out}$ of the bridge circuit. We compute the change in $Y_{DUT}$ from the deviation of $v_{out}$ and $v_{th}$ away from the balancing point using Eq. 1. As the DC output of the circuit $v_{out}$ does not vary while sweeping $V_{DUT}$ but the phase of $v_{out}$ does (see Figs. 5g and H), we model the complex admittance $Y_{DUT}$ by a capacitor and a resistor in series. We split this capacitance into the geometric capacitance of the top gate to the graphene and the quantum capacitance due to a finite density of states in graphene. The resistance is attributed to a resistance in the graphene sheet and a contact resistance.

IV. RESULTS AND DISCUSSION

Graphene exhibits an electronic bandstructure, where the conduction and the valence band touch in (two) so-called Dirac points.\textsuperscript{28} The energy-momentum relation is linear around each Dirac point which directly results in a linearly varying density of states and thus a quantum capacitance $C_q$ that linearly varies with the Fermi energy.\textsuperscript{28} The quantum capacitance has a minimum when the Fermi energy aligns with the Dirac points.\textsuperscript{11} We control the Fermi energy by the bias $V_{DUT}$ applied to the top gate. When the Fermi energy is far away from the Dirac point, the density of states and thus $C_q$ will be large such that the geometric capacitance $C_g$ dominates. In case of an externally applied magnetic field, discrete Landau levels emerge in the electronic band structure of graphene.\textsuperscript{28} Consequently, the density of states and thus $C_q$ shows a minimum when the Fermi energy is tuned between two bulk Landau levels. The resistance $R_{DUT}$ is expected to show a maximum when $C_q$ is minimum due to the absence of states that can contribute to transport.\textsuperscript{10,12}

Figures 5f-h show the extracted graphene capacitance and resistance as a function of applied gate bias $V_{DUT}$ and magnetic field for our integrated impedance bridge at 60 mK. The $V_{DUT}$ has been shifted by -0.29 V to compensate for the gate bias of the HEMT. The measurement was performed with a small $v_{DUT}$ of 59.3 µV or 12.9 $k_B T/e$, which resulted in resolutions of 4.1 kΩ/$\sqrt{Hz}$ and 1.7 pF/$\sqrt{Hz}$. This capacitance resolution is for the given $v_{DUT}$ similar to those obtain using an LCR meter.\textsuperscript{26} We observe the emergence of Landau levels in both the extracted $C_{DUT}$ and $R_{DUT}$ with increasing applied magnetic field as dips and peaks, i.e. see line traces in Figs. 5f and 5g. Even far below 1 T, we can observe the formation of Landau levels (see Fig. 5h), which illustrates the good quality of the device. The overall capacitance and resistance curves thus show the trend expected from the electronic band structure of graphene and is in agreement with graphene capacitance and transport measurements reported in the literature.\textsuperscript{10,12} The measured $C_{DUT} \sim 0.3$ pF is slightly higher than the expected parallel plate capacitance. Note that the difference is about equal to that observed for the comb-drive actuator above. To understand this further, we extracted the slope of the features in $C_{DUT}$ and $R_{DUT}$ (see black dashed lines in Figs. 5g and 5h) and we extract the so-called lever arm, which results in a capacitance of 0.24 pF. Interestingly, this value is in agreement with the parallel plate capacitance and it is also lower than the measured capacitance, which suggests the presence of a parasitic capacitance in parallel to the top gate capacitance due to the presence of the other gates. Note that the observed change in capacitance on the order of 0.1 pF is smaller than the parallel plate capacitance and is, therefore, in agreement with this picture. The unexpectedly high values of $R_{DUT}$ indicate the presence of a large resistance that is in series to the resistance of the top gated area and a contact resistance, which likely originates from the large graphene area not biased by the top gate (see Fig. 5h).

V. CONCLUSION

We designed and constructed an integrated impedance bridge that operates from room temperature down to 50 mK temperatures. By placing the HEMT parallel to the externally applied magnetic field, the integrated impedance bridge keeps its functionality in magnetic fields up to at least 12 T. We find the best resolution when operating the HEMT at the highest gain. All measurements in this work were performed with excitation amplitudes close to the order of $k_B T/e$ to ensure minimal heating of the electronic system. The presented approach enables direct measurements of the capacitance in micro-electromechanical systems such as comb-drive actuators.
and can thus be used to estimate their displacement or motion. Using a hBN/graphene/hBN heterostructure, we showed that the presented approach can be used to simplify the analysis of transport experiments on systems with a low density of states such as 2D materials.

VI. ACKNOWLEDGEMENTS

The authors acknowledge S. Bosco for proof reading the manuscript. Supported by the ERC (GA-Nr. 280140), the Helmholtz Nano Facility (HNF) at the Forschungszentrum Jülich, the Deutsche Forschungsgemeinschaft (DFG) (SPP-1459), and the EU project Graphene Flagship (Contract No. 696656) are gratefully acknowledged. G.V. acknowledges funding by the Excellence Initiative of the German federal and state governments. K.W. and T.T. acknowledge support from the Elemental Strategy Initiative conducted by the MEXT, Japan and the CREST (JPMJCR15F3), JST.

1"International technology roadmap for semiconductors," ITRS Technical Report, 2015.

2S. Datta, Quantum Transport: Atom to Transistor (Cambridge University Press, Cambridge, 2007).
3S. Luryi, Appl. Phys. Lett. 52, 501 (1988).
4D. L. John, L. C. Castro, and D. L. Pulffrey, J. Appl. Phys. 96, 5180 (2004).
5M. Goldsche, J. Sonntag, T. Khodkov, G. J. Verbiest, S. Reichardt, C. Neumann, T. Ouaj, N. von den Driesch, D. Buca, and C. Stampfer, Nano Lett. 18, 1707 (2018).
6M. Goldsche, G. J. Verbiest, T. Khodkov, J. Sonntag, N. von den Driesch, D. Buca, and C. Stampfer, Nanotechnology 29, 375301 (2018).
7J. Xia, F. Chen, J. Li, and N. Tao, Nature Nanotechnol. 4, 505 (2009).
8S. Dröschler, P. Rouleau, F. Molitor, P. Studerus, C. Stammer, T. Ihn, and K. Ensslin, Appl. Phys. Lett. 96, 152104 (2010).
9X. Chen, L. Wang, W. Li, Y. Wang, Z. Wu, M. Zhang, Y. Han, Y. He, and N. Wang, Nano Research 6, 619 (2013).
10G. L. Yu, R. Jalil, B. Belle, A. S. Mayorov, P. Blake, F. Schedin, S. V. Morozov, L. A. Ponomarenko, F. Chiappini, S. Wiedmann, U. Zeitler, M. I. Katsnelson, A. K. Geim, K. S. Novoselov, and D. C. Elias, Proc. Natl. Acad. Sci. 110, 3282 (2013).
11"Graphene science handbook: size-dependent properties" (CRC Press), Chapter 13, G. S. Kliros (2015).
12A. A. Zibrov, E. M. Spanton, H. Zhou, C. Kometter, T. Taniguchi, K. Watanabe, A. F. Young, Nat. Phys. 14, 930 (2018).
13S. Iani, L. A. K. Donev, M. Kindermann, and P. L. McEuen, Nat. Phys. 2, 687 (2006).
14T. P. Smith, B. B. Goldber, P. J. Stiles, and M. Heiblum, Phys. Rev. B 32, 2696 (1985).
15F. Stern, Appl. Phys. Lett. 43, 974 (1983).
Agilent Technologies, Inc., *Impedance Measurement Handbook* (Agilent Technologies, 2009).

M. C. Foote and A. C. Anderson, Rev. Sci. Instrum. **58**, 130 (1986).

C. G. Andeen and C. W. Hagerling, U.S. patent 4,772,844 (1988).

A. Gokirmak, H. Inaltekin, and S. Tiwari, Nanotechnology **20**, 335203 (2009).

R. C. Ashoori, H. L. Stormer, L. N. Pfeiffer, S. J. Pearton, K. W. Baldwin, and K. W. West, Phys. Rev. Lett. **68**, 3088 (1992).

J. Martin, N. Akerman, G. Ulbricht, T. Lohmann, J. H. Smet, K. von Klitzing, and A. Yacoby, Nat. Phys. **4**, 144 (2008).

A. Hazegi, J. A. Sulpizio, G. Diankov, D. Goldhaber-Gordon, and H. S. P. Wong, Rev. Sci. Instrum. **82**, 053904 (2011).

The HEMT is manufactured by the Fujitsu Corporation.

The voltage controlled capacitor is manufactured by ON Semiconductor.

L. Banszerus, M. Schmitz, S. Engels, J. Dauber, M. Oellers, F. Haupt, K. Watanabe, T. Taniguchi, B. Beschoten, and C. Stampfer, Sci. Adv. **1**, e1500222 (2015).

M. I. Katsnelson, *Graphene: Carbon in Two Dimensions* (Cambridge University Press, New York, 2012).

Research Center Jülich GmbH. (2017). HNF - Helmholtz Nano Facility, *Journal of large-scale research facilities* **3**, A112 (2017).