An RF Circuit Model of a Quantum Point Contact

Sungmu Kang, Chris Rutherglen, Nima Rouhi, Peter Burke, *Member, IEEE*, L. N. Pfeiffer, and K. W. West

***Abstract*—We develop a realistic, physics based, practical RF circuit model for the AC impedance of a quantum point contact that includes the ohmic contacts, the on-chip "lead" resistance and kinetic inductance, and the quantum point contact impedance itself. The kinetic inductance of the electrons in the "leads" in series with the quantum point contact capacitance form a resonant tank circuit whose resonant frequency depends on the width of the quantum point contact channel. These measurements probe devices in the following qualitative regime: They are in the ballistic limit, and the measurement frequency is higher than the electron scattering frequency.**

***Index Terms*—GaAs, Quantum Point Contact, RF circuit model.**

BALLISTIC electron transport in the spatial limit occurs when the device size is smaller than the mean free path. The canonical example of such a device is a QPC, although carbon nanotubes have recently demonstrated ballistic transport up to 1 μm even at room temperature [1], [6]. We recently showed [2]–[4] that in the frequency domain, it is also possible to study electron transport in the range where the measurement frequency ω is larger than the scattering frequency $1/\tau$. In this paper, we provide measurements of the ac impedance in a system that is ballistic in both senses: The sample size is larger than the mean free path, and measurement frequency is larger the scattering rate.

The kinetic inductance of the electrons in the "leads" in series with the QPC capacitance forms a resonant tank circuit whose resonant frequency depends on the width of the QPC channel. Implications for the concept of the ac impedance of a nanodevice are discussed in the conclusions. We develop a realistic, physics-based, practical RF circuit model for the ac impedance of a QPC that includes the ohmic contacts, the on-chip 2-D electron gas (2DEG) "lead" resistance and kinetic inductance, and the QPC impedance itself.

The QPC is fabricated from a GaAs/AlGaAs modulation-doped single quantum well grown by molecular beam epitaxy. Rapid annealing at 440 °C follows after Ni/Ge/Au/Ni/Au ohmic metallization (80:270:540:140:2000 Å). Ti/Au (200:800 Å) depletion gates are deposited using electron beam lithography and

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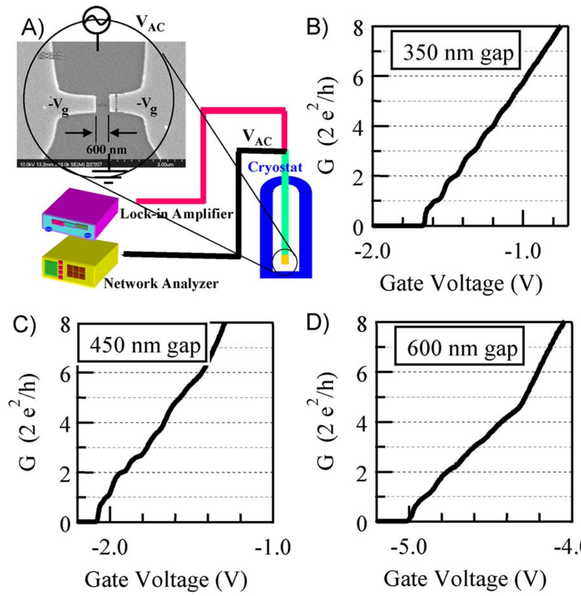

Fig. 1. (a) Measurement setup of QPC with 600 nm gap and (b)--(d) measured quantized conductance of QPC with different gaps at 4 K.

a liftoff process. The measurement setup and geometry device are shown in Fig. 1, and the gap varies from 350 to 600 nm. After illumination with a red LED, the mobility based on dc measurements of samples from the same wafer is 13×10^6 and 6×10^6 $cm^2/V \cdot s$ at 0.3 and 4 K, respectively, while the electron density is $\sim 2.0 \times 10^{11}/cm^2$.

For the ac measurements, the sample is mounted at the end of a 50-Ω matched microstrip line. A variable negative voltage is applied to both depletion gates; dc conductance is measured using a lock-in analyzer at 13 Hz. The measured dc conductance quantization is demonstrated in Fig. 1. The device impedance $Z(\omega)$ is determined by measuring the RF refection coefficient S_{11} with a network analyzer. Z (ω) and S_{11} are related by the standard expression

$$S_{11} = \frac{Z - 50\,\Omega}{Z + 50\,\Omega}. \tag{1}$$

In our experiments, there is some RF loss from the microwave generator to the terminals of the device. These were independently determined by measuring the loss of the coax in a separate experiment. The detailed calibration method was presented in previous reports [3], [4]. Because of the device high impedance, the calibrations are not accurate, especially regarding the separation of the real and imaginary parts of the impedance. For this reason, we focus mostly on analyzing the magnitude of S_{11}, which is less sensitive to calibration errors.

In Fig. 2, we plot the measured magnitude of S_{11} (in dB) versus frequency for various gate voltages. By varying the

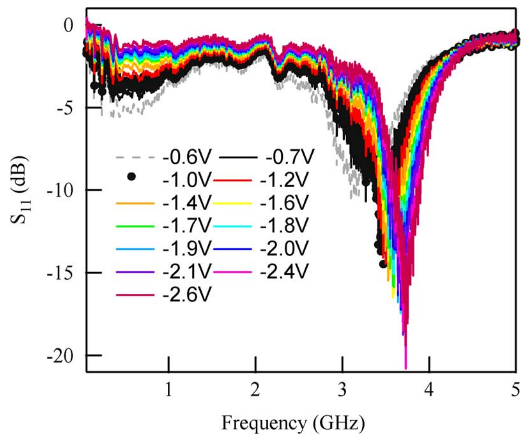

Fig. 2. Measured S_{11} of QPC at 4 K.

gate voltage only, we expect the contact resistance and on-chip "lead" resistance and kinetic inductance to remain constant, so that the only physical quantity changing is the QPC impedance. In addition, however, the width of the ungated region away from the QPC will change slightly, which may change the parasitic capacitance in parallel with the QPC slightly. In the RF data, a clear resonance is apparent at around 3–4 GHz, which is discussed next. This frequency is well above the scattering frequency $(1/\tau)$, which, for these samples (mobility $\sim$6 $\times$ 10^6 cm^2/V-s, $\tau \sim 210$ ps), is 4.7×10^9 rad/s ($\omega = 2\pi$f) or $\sim$0.7 GHz in frequency.

By fitting the resonance, we can determine the resonance frequency versus gate voltage, which we plot in Fig. 3. Starting from complete pinch off ($\text{width of channel} = 0$, corresponding to no propagating modes), the resonance frequency changes gradually. Once the region under the gates is no longer pinched off (~ -0.5 V), the frequency dramatically shifts with gate voltage, as the entire chip is now carrying current. When there is no channel (i.e., when the regions under the gate is full of electrons, so the current can flow freely everywhere in the plane), the resonance disappears. This is consistent with our recent measurements on ungated 2DEGs [3], [4]. When the channel is entirely pinched off, the resonance is still present. This is likely because of the parasitic capacitance (and not the intrinsic QPC capacitance), which we discuss next.

In order to explain these results, we show in Fig. 4 an effective RF circuit model for a QPC. We now explain the specific components of the circuit: The kinetic inductance is due to the 2DEG in the region between the ohmic contact and the QPC. The resistance is $R_{\rm 2DEG}$ due to the 2DEG resistance between the ohmic contact and the QPC. The contact resistance is due to the annealed Au/Ni/Ge evaporated ohmic contacts. These elements are present on both sides of the QPC. The QPC has a resistance and capacitance, and there is also a fringe field capacitance from one side of the QPC to the other. Note that an *RL* circuit along will not produce a resonance. The 3.5 GHz resonance is due to the *L* and *C* values causing the imaginary part of the impedance to vanish on resonance. The wire bond inductance is estimated for our geometry, and the on-chip "lead resistance" is due to the 2DEG feeding the QPC. Here, $R_{\rm 2DEG} = (L/W)*m*/(ne^2\tau)$ and $L_{\rm kinetic} = (L/W)*m*/(ne^2)$, where

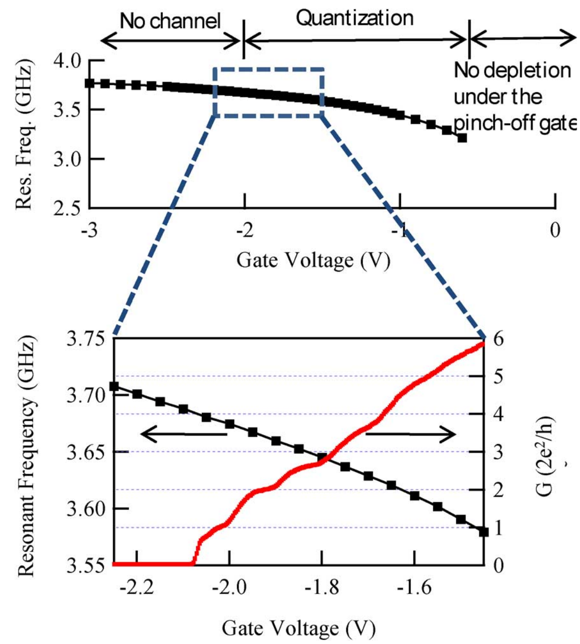

Fig. 3. Measured resonant frequency (left axis) and dc conductance (right axis) versus gate bias voltage.

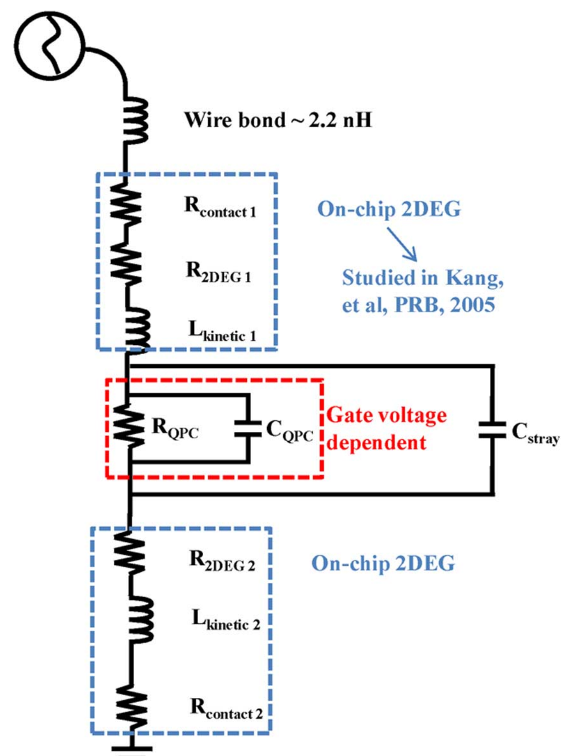

Fig. 4. RF circuit model of a QPC.

n is number of electrons (2.0×10^{15}/cm^2), $e = 1.602 \times 10^{-19}$C, $m* = 0.067 \times 0.9 \times 10^{-30}$ kg, and the 2DEG geometry is 2 mm $\times$ 2.5 mm. Detailed values are described in Table I. The total capacitance $C_{\rm QPC}||C_{\rm stray}$ is determined from the resonant peak frequency value. There is also an ohmic contact resistance, which we have studied in a separate publication [3]. The total dc contact resistance $(= R_{\rm contact1} + R_{\rm contact2})$ is 30 Ω, while $R_{\rm 2DEG}$ is 6 Ω.

TABLE I
ELEMENTS OF THE EQUIVALENT CIRCUIT

$L_{\text{wire bond}} = 2.2$ nH	$L_{\text{kinetic 1}} = 0.46$ nH	$L_{\text{kinetic 2}} = 1$ nH
$R_{\text{contact 1}} = 15\ \Omega$	$R_{\text{2DEG 1}} = 2\ \Omega$	V_G dependent R_{QPC}
$R_{\text{contact 2}} = 15\ \Omega$	$R_{\text{2DEG 2}} = 4\ \Omega$	V_G dependent C_{total} (= $C_{QPC} \parallel C_{\text{stray}}$)

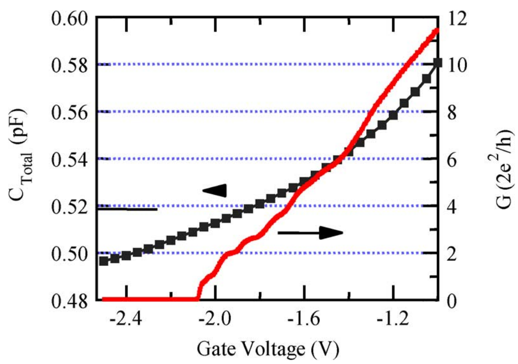

Fig. 5. (Left) Estimated QPC capacitance from resonant frequency and (right) dc conductance versus gate voltage.

Based on this physically derived model, we can predict that only R_{QPC} and C_{QPC} will vary as the gate voltage (V_G) is varied. In our measurements, the calibrations are not sensitive to R_{QPC} (so long as it is larger than $\sim$kΩ, which it is), and so the exact value of R_{QPC} cannot be determined. However, C_{QPC} has a large impact on the resonance frequency, which is easily measured. In Fig. 5, we plot the inferred value of $C_{\mathrm{QPC}} \| C_{\mathrm{stray}}$ from the measured resonance frequency. The value of $C_{\mathrm{QPC}} \| C_{\mathrm{stray}}$ is similar to that measured at 1 MHz using a capacitance bridge. The dependence of the value of C_{QPC} on the gate voltage (or # of quantum channels) is predicted to be very nonlinear, and to change dramatically as a new channel is added. In addition, the electron density in the bulk regions is also not linear with the gate voltage, and so fringe field capacitance also is not expected vary linearly with the gate voltage.

We now discuss possible physical origins of the capacitance. The capacitance from 2DEG to the ground plane is of order picofarad, but does not vary with pinch off voltage, and has no effect on the resonance, and so can be ruled out as the origin of the changing capacitance. In fact, we studied the on-chip effective circuit model of the 2DEG in detail and found the *RL* circuit to be an accurate equivalent circuit model for the geometry studied there, and found no resonances in the 2DEG on-chip impedance. (In that work where an *RL* circuit model was appropriate, there was no QPC. In contrast, in this paper, there is a QPC, so an *RLC* circuit model is more appropriate.) In fact, the sample studied here was originally studied in [4] (prior to the fabrication of the QPC electrode, and after that study, the pinch-off electrodes were deposited to define the QPC. Therefore, the resonance is not from the on-chip 2DEG capacitance to ground.

The change in the capacitance can be due to the inherent QPC capacitance (predicted [5] and [7]–[10] to be of order fF per quantum channel) or due to a change in the parasitic capacitance from reservoir to reservoir. An estimate for this parasitic capacitance based on the chip geometry is $\sim$ 0.1 pF, which is the same order of magnitude of the measured total capacitance. However, the change in the fringing capacitance with gate voltage should be much less, since the depletion region changes by a relatively small amount with gate voltage. What is clear is that changing the gate voltage changes the capacitance by $\sim$ 10 fF per quantum channel, which is in the range of predicted "intrinsic" QPC capacitance values of 1 fF per quantum channel. Thus, the most likely explanation of the origin of the capacitance is that the overall capacitance consists of the fringing field capacitance between electrodes, in parallel with the "intrinsic" QPC capacitance. Changing the gate voltage changes the intrinsic QPC capacitance in a measurable way that is consistent in magnitude with theoretical predictions. However, we cannot rule out the possibility that this change in capacitance is a change in the fringe field capacitance with gate voltage. The fact that the capacitance changes with gate voltage about the same way both when there are finite #s of channels and when there are no channels seems to indicate this is a possibility.

With improved calibration techniques, it should in principle be possible to determine if the ac conductance is quantized at frequencies in the limit $\omega < 1/\tau$ or $\omega > 1/\tau$. We note that there is no theory for the ac conductance of a ballistic QPC in the limit $\omega > 1/\tau$, and thus our measurements probe a regime of device operation without clear theoretical predictions. A more general conclusion of our work relates to the definition of a "device" at AC. Just as one cannot define a precise spatial boundary where an ideal ballistic conductor begins and the phase randomizing reservoirs end, also at AC one cannot easily draw an imaginary line and separate the device from its electromagnetic environment. Rather, the fringe capacitance as well as the capacitance of the device itself must be considered as part of one complete system.

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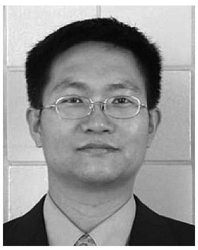

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