ac ballistic transport in a two-dimensional electron gas measured in GaAs/AlGaAs heterostructures

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We measure the crossover from diffusive to ballistic transport as a function of frequency in dc contacted high-mobility two-dimensional electron gas structures in GaAs/AlGaAs heterostructures at GHz frequencies. By systematically measuring samples of varying mobility we demonstrate that the crossover frequency scales with mobility as predicted by the Drude model. We find the ohmic contact impedance to be real and independent of frequency for samples with mobility higher than 500 000 cm^2/V s, while there is a significant capacitive component in parallel with the contact resistance for lower mobility samples.

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I. INTRODUCTION

The Drude model predicts a frequency dependent conductivity (in the limit the wave vector $k \rightarrow 0$) given by

$$\sigma(\omega) = \frac{ne^2\tau}{m^*}\frac{1}{1+i\omega\tau}, \tag{1}$$

where n is the electron density, m^* the effect mass, and τ the transport scattering time. Scattering typically occurs via electron-phonon (temperature dependent) and electron-impurity (temperature independent) scattering. For dirty metals, $\omega\tau \sim 1$ at optical frequencies at both room and cryogenic temperatures. In bulk $(3d)$ semiconductor materials at room temperature, $\omega\tau \sim 1$ at frequencies of order 500–800 GHz (including Si, GaAs, InP). In two-dimensional electron gas systems (2DEGs), ionized donors can be set back from a quantum well which forms the 2DEG, allowing higher mobility due to this donor setback. At cryogenic temperatures, this can lead to mobilities of order 10^7 cm^2/V s, which corresponds to $\omega\tau \sim 1$ at frequencies of order 1 GHz. This also leads to mean-free paths $(l = v_F\tau)$ of order microns.

For these high-mobility systems, extensive measurements of dc transport have allowed a large variety of quantum transport devices to be studied at cryogenic temperatures under controllable conditions due to the fact that ballistic transport can be achieved in lithographically defined structures because the mean-free path is of order microns.[1] These include, for example, quantum dots, single-electron transistors, quantum point contacts, and even qubits. The physics learned during these studies at cryogenic temperatures under controlled conditions is now being translated into interpreting room-temperature behavior of various nanoelectronic devices, where fabrication and even spatial characterization are a challenge.

In contrast, there has been relatively little work done to investigate quantum transport in high-mobility systems in the limit $\omega\tau \sim 1$. This can also be considered ballistic transport, since electrons do not scatter during a typical electric field cycle. There is a technological motivation to better understand ballistic transport in this limit for two reasons: First, ballistic transport in the spatial limit will need to be carefully studied and modeled[2–8] at room temperature for nanotransistors to become a widely used technology.[9] There, finite time-of-flight effects may already limit the mobility achievable,[10] which would have implications for the operational frequency of these nanotransistors. A second, more long time motivation is that new modes of transistor operation (separate from field-effect) may be possible[11] at room temperature in the limit $\omega\tau > 1$, i.e., at THz frequencies. However, because characterization of the regime $\omega\tau > 1$ is difficult at THz frequencies at room temperature, measurements of device operation at GHz frequencies at cryogenic temperatures allow controllable, quantifiable tests of quantum transport in the limit $\omega\tau > 1$. Finally, at cryogenic temperatures, it is possible (although not studied here) to quantitatively investigate quantum transport in the ballistic limit both in the sense that the sample size is smaller than the mean-free path, and in the limit $\omega\tau > 1$.

In this research, we systematically study the effect of the dc mobility on ac transport in GaAs 2DEGs at low electric fields. In previous work,[12] we characterized ballistic transport with capacitive contacts. Later, we characterized transport in dc contacted samples at one mobility.[13] Here we present a systematic study of the ballistic transport in the limit $\omega\tau \sim 1$ as a function of sample mobility. We also demonstrate 2DEG ac transport measurements where the scattering time is below 1 GHz. This paper presents a systematic study and demonstration of the effect of the dc mobility on the ac properties of ohmic contacted 2DEG systems and the crossover from ballistic to diffusive transport. We demonstrate that the crossover frequency from ballistic to diffusive transport scales with dc mobility in ohmic contacted 2DEG systems.

II. THEORY AND BACKGROUND

For a 2DEG sample in which the ohmic contact resistance is negligible, the impedance $Z_{2DEG}(\omega)$ can be written as

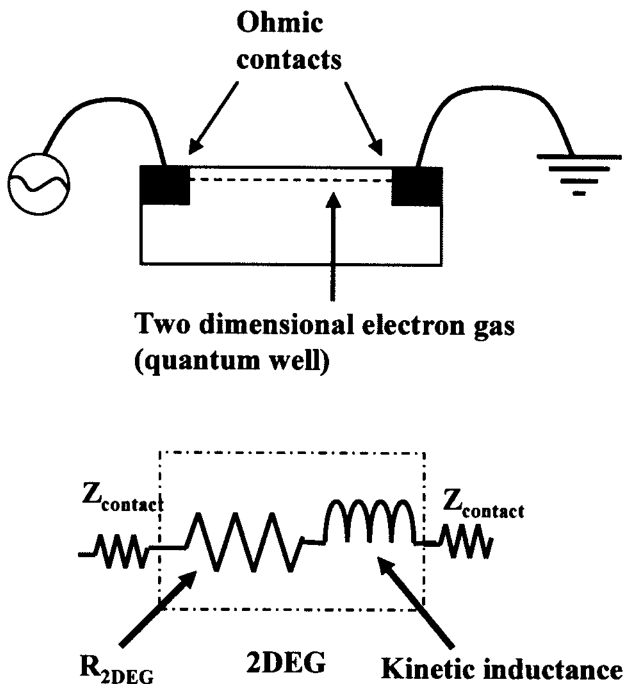

FIG. 1. Measurement geometry and low field ac equivalent circuit.

$$Z_{2\mathrm{DEG}}(\omega) = R_{2\mathrm{DEG}} + i\omega L_k, \quad (2)$$

where $L_k=m^*/(ne^2)$ per square is called the kinetic inductance and $R_{2\mathrm{DEG}}=m^*/(ne^2\tau)$ per square is the dc resistance. This model predicts two testable features. First, the real impedance is frequency independent and equal to the dc resistance. Second, at $\omega\tau=1$, $\mathrm{Re}(Z_{2\mathrm{DEG}})$ is equal $\mathrm{Im}(Z_{2\mathrm{DEG}})$. This is indicated schematically in Fig. 1.

In the more general case where the ohmic contact resistance is finite, the ac impedance is given by

$$Z(\omega) = Z_{\mathrm{contact}}(\omega) + Z_{2\mathrm{DEG}}(\omega). \quad (3)$$

In general, the contact impedance Z_{contact} is difficult to predict and must be measured experimentally. This is especially true in the limit $\omega\tau=1$. When the contact resistance is finite, the dc resistance cannot be uniquely measured. However, it can be predicted with reasonable certainty based on the sample geometry and measurements of the sample mobility and density from different pieces of the same MBE grown wafer.

Equation (2) applies in the limit $k\rightarrow 0$, even though our experimental sample length (and hence wave vector) is finite. Ryzhii[14] has theoretically analyzed the effect of a finite wave vector on the impedance of an ungated 2DEG, and finds that our simple model [Eq. (2)] is approximately correct in the limit $f=\omega/2\pi \ll (\pi^2 e^2 n/m\varepsilon L)^{1/2}/2\pi \approx 22$ GHz, where we have used an electron density of $n=2\times 10^{11}$ cm^{-2} and sample length of 5 mm, appropriate for our measurement geometry. Since our measurement frequencies are well below this frequency, the use of Eq. (2) in our model is justified.

III. FABRICATION

The samples studied are GaAs/AlGaAs modulation doped quantum wells grown by molecular beam epitaxy. After MBE growth samples were patterned using direct cleaving into a geometry of order 2×5 mm. The structures were engineered to have nominally the same electron density of 2×10^{11} cm^{-2}. The geometry was adjusted to achieve a dc resistance of close to 50 Ω for compatibility with the microwave measurement system. Ohmic contacts were formed by evaporating a Ni/Ge/Au/Ni/Au multilayer (80/270/540/140/2000 Å) on both ends of the ungated structure. Rapid thermal annealing was performed at 440 °C with forming gas (10% hydrogen and 90% nitrogen). The annealing time for each sample was almost the same, but adjusted for each sample to get optimum contact resistance. Samples with mobility below 573 000 cm^2/V (samples 1 and 2) were annealed for 14 and 13 min, respectively. Samples with mobility above 573 000 cm^2/V s (samples 3–8) were annealed for 12 min.

IV. MEASUREMENT AND CALIBRATION TECHNIQUE

In order to characterize the impedance of a two-dimensional electron gas with different mobility, we measure both the dc and ac impedance. The dc impedance is measured using lock-in amplifier (SR810) at 13 Hz by applying 1 μA to the sample. The sample is mounted on the end of a 50 ohm matched microstrip line using In solder. The ac impedance (both real and imaginary) is determined by measuring the microwave reflection coefficient $S_{11}(\omega)\equiv V_{\mathrm{reflected}}/V_{\mathrm{incident}}$ off of the sample at 4 K and inverting the standard microwave reflection coefficient $S_{11}=[Z(\omega)-50\ \Omega]/[Z(\omega)+50\ \Omega]$. We calibrate up to the tip of coaxial cable with known calibration standards (open, short, and load). The detailed calibration technique is explained in Ref. 13. The ac impedance is measured by both an rf (13–500 MHz) network analyzer (4395 A) and a microwave (50 MHz to 10 GHz) network analyzer (8720 ES). At the power levels used (100 nW), the results are independent of the power used.

The experimentally measured quantity includes both the 2DEG impedance and the contact impedance. At dc, the 2DEG resistance $R_{2\mathrm{DEG}}$ can be calculated based on the geometry and the sheet resistance determined from other samples on the same wafer. The dc contact resistance R_{contact} can be determined by subtracting the 2DEG resistance from the measured dc resistance R_{dc}.

At ac, the frequency at which $\mathrm{Re}(Z_{2\mathrm{DEG}})=\mathrm{Im}(Z_{2\mathrm{DEG}})$ corresponds to $\omega\tau=1$. The value of τ can also be determined from the dc measured mobility through the relationship $\mu = e\tau/m^*$. If the contact impedance is negligible then the frequency at which the measured $\mathrm{Re}(Z)$ crosses $\mathrm{Im}(Z)$ allows direct determination of the crossover from $\omega\tau<1$ to $\omega\tau>1$ and, hence, the crossover from ballistic to diffusive transport.

V. RESULT AND DISCUSSION

We measured the dc and ac impedance of eight different samples and the results are summarized in Table I. For al-

TABLE I. Summary of measured dc and ac impedance values.

Sample	Mobility ($cm^2/V\,s$)	R_{2DEG} (Ω)	$R_{contact}$ (Ω)	R_{dc} (Ω)	$Re(Z)_{ac}$ (Ω)	$\tau_{dc} \equiv \mu m^*/e$ (ps)	τ_{ac} (ps)
1	36 000	47	63	110	49	1.4	<1.0
2	150 000	69	36	105	70	5.7	<4.5
3	573 000	42	5	47	46	22	19
4	573 000	36	8	44	42	22	19
5	2.45×10^6	41	14	55	55	93	90
6	3.23×10^6	25	13	38	38	118	106
7	5.87×10^6	7	6	13	13	224	200
8	6.00×10^6	8	6	14	14	229	210

most all of these samples the contact resistance at dc $R_{contact}$ was comparable to the 2DEG resistance at dc R_{2DEG}. The total resistance at dc R_{dc} varied between 10 and 110 Ω. For all of the samples measured, $Re(Z)$ (which includes, in principle, the contact impedance and the 2DEG impedance) was independent of frequency at frequencies higher than 100 MHz. In Table I this is referred to as $Re(Z)_{ac}$. Additionally, for all samples studied, the imaginary part of the impedance $Im(Z)$ was inductive, i.e., proportional to frequency, over the frequency range studied.

The correlation between the dc resistance and the ac real impedance fell into two classes. For devices 3–8 the dc resistance was numerically equal to the ac real impedance. This can be seen in the table. For devices 1 and 2, the dc resistance was larger than the ac real impedance. We focus first on devices 3–8.

In Fig. 2 we plot the measured impedance vs frequency for sample 6. The imaginary component is inductive, and the real part is nominally independent of frequency and equal to its dc value. Based on the known mobility of this sample we can calculate the scattering time using the relationship $\mu = e\tau/m^*$. We name the value of τ so calculated τ_{dc}, to indicate that it is inferred from dc transport measurements. For the mobility of 3.23 10^6 $cm^2/V\,s$, the calculated value of τ is 118 ps. Based on the Drude model, this should be related to

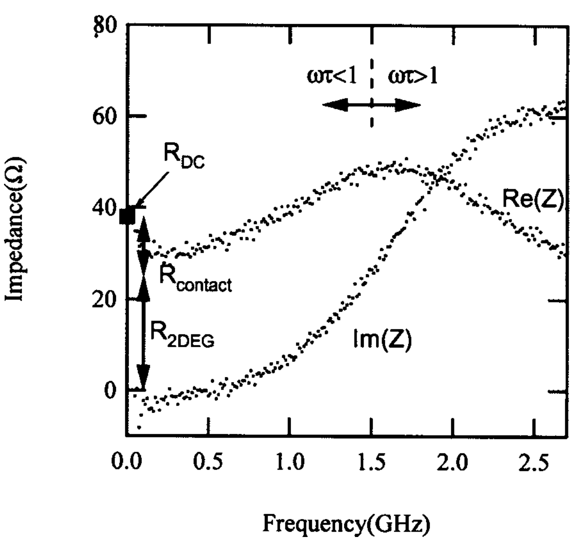

FIG. 2. Impedance vs frequency for sample 6.

the frequency at which $Re(Z_{2DEG}) = Im(Z_{2DEG})$; this should occur at a frequency corresponding to $\omega\tau = 1$, or at 1.35 GHz for this sample. We find that, for this sample, $Re(Z) = R_{2DEG} + R_{contact}$, i.e., that the contact impedance is real and frequency independent, consistent with our prior work.[13] Thus, by subtracting $R_{contact}$ from the measured value of $Re(Z)$, we can determine $Re(Z_{2DEG})$. By measuring the frequency at which $Re(Z_{2DEG}) = Im(Z_{2DEG})$, we determine the frequency at which $\omega\tau = 1$ experimentally; this crossover frequency is indicated in Fig. 2. The value of τ determined using this method is termed τ_{ac}. For this sample we find a value of 106 ps, consistent with the value determined from dc transport measurements.

Similar results and conclusions are found for all of samples 3–8, which spans a mobility of one order of magnitude. Table I shows good agreement between the dc resistance and the measured real impedance at microwave frequencies for these samples, indicating that the contact resistance is real, independent of frequency, and equal to its dc value. In addition, scattering time determined using dc transport experiments (τ_{dc}) is equal to the scattering time using ac transport experiments (τ_{ac}), as seen also in Table I. Thus we have demonstrated the crossover from diffusive to ballistic transport as a function of frequency, and demonstrated that the crossover frequency scales with mobility as predicted by the Drude model.

We now turn our attention to samples 1 and 2, both of which had mobilities below 200 000 $cm^2/V\,s$. For these samples, the predicted frequency at which $Re(Z_{2DEG}) = Im(Z_{2DEG})$ is $\sim$100 GHz based on the scattering time inferred from the mobility, which is out of the range of our measurement system. Consequently $Re(Z_{2DEG})$ is expected to be independent of frequency and equal to its dc value, and $Im(Z_{2DEG})$ is expected to be approximately zero.

In contrast to samples 3–8 with somewhat higher mobility, the contact impedance to samples 1 and 2 is frequency dependent, and contains an imaginary component. This is clearly seen in Fig. 3, where we plot the measured impedance vs. frequency for sample 1. At frequencies above 0.1 GHz the real impedance is equal to the 2DEG resistance R_{2DEG}. However, at low frequencies there is a significant contact resistance, which decays with increasing frequency. Experimentally, we find that the measured ac impedance can be described by

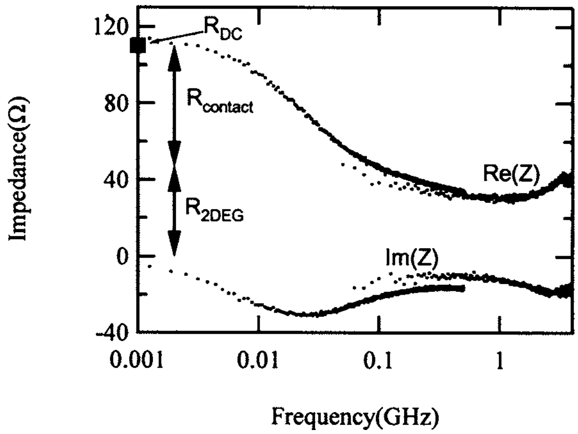

FIG. 3. Impedance vs frequency for sample 1.

$$Z(\omega) = \frac{R_{\mathrm{contact}}}{1 + i\omega R_{\mathrm{contact}}C} + R_{\mathrm{2DEG}} + i\omega L_k, \tag{4}$$

where R_{contact} is the dc contact resistance (measured) and C is a phenomenological capacitance. For sample 1, the value of C which best fits the data is 85 pF. At the moment the physical origin of this contact is not known, but it is clearly related to the mobility. Samples 1 and 2 both show this effect, whereas samples 3–8 do not.

Finally, in Fig. 4, we plot the impedance vs. frequency for sample 8, the highest mobility sample measured. For this sample, the crossover frequency is about 700 MHz, which is the first measurement of ballistic transport (i.e., $\omega\tau > 1$) at frequencies under 1 GHz. This sample, when combined with lithographically defined nanostructures, will provide an excellent testbed for high frequency ballistic quantum transport in devices such as, for example, quantum point contacts. The low scattering frequency simplifies the rf calibrations and other experimental requirements. Ultimately it may be possible to measure individual electron scattering events in real time on samples from this wafer, which would allow a new window on exploring quantum transport in semiconductor nanostructures.

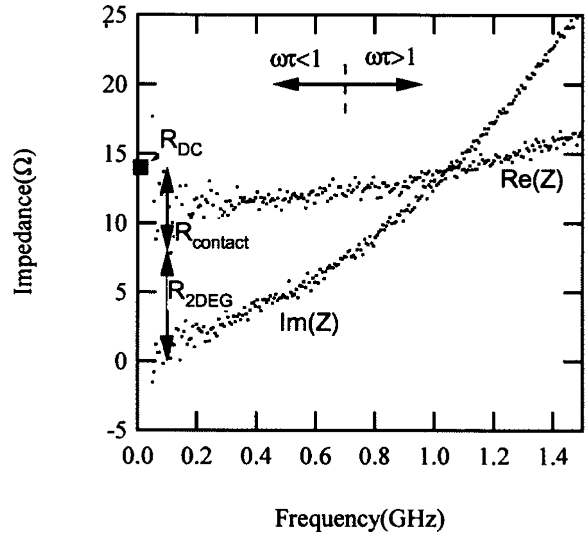

FIG. 4. Impedance vs frequency for sample 8.

VI. CONCLUSION

We have systematically measured the effect of the dc mobility on ac ballistic transport of ungated 2DEGs with different contacts. For samples with mobility larger than 500 000 $\mathrm{cm}^2/\mathrm{V\,s}$, we have demonstrated the crossover from diffusive to ballistic transport as a function of frequency, and demonstrated that the crossover frequency scales with mobility as predicted by the Drude model. Additionally, for this mobility range, the ohmic contact impedance is real, independent of frequency, and equal to its dc value. In contrast, for lower mobility samples the ohmic contact impedance has a significant capacitive component which is shorted out at frequencies above $\sim$100 MHz. Future work will include measurements in the ballistic regime in both the sense that $\omega\tau > 1$ and the sample size > mean-free path, as well as possibly real-time measurements of individual scattering events, opening a new window on quantum transport in semiconductor nanostructures.

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