Student Paper

Crossover from diffusive to ballistic transport as a function of frequency in a two dimensional electron gas

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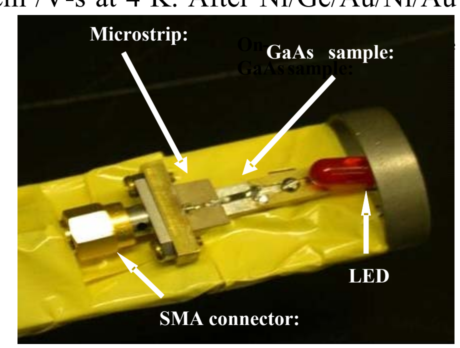
We measure for the first time the crossover from diffusive ($\omega\tau_m<1$) to ballistic ($\omega\tau_m>1$) transport as a function of frequency (dc to 10 GHz) in a dc contacted 2DEG. (τ_m is the momentum scattering time.) Here, ballistic transport is defined as electron transport in the limit ($\omega\tau_m>1$); the electrons move without scattering (ballistically) between electric field cycles. Diffusive transport can be defined as the lower frequency range ($\omega\tau_m<1$); in the diffusive limit there are many scattering events between electric field cycles. The measurements presented here are for ungated geometries, but the motivation is to move later to gated geometries. In gated geometries in the limit ($\omega\tau_m>1$), ballistic effects can be used for a new class of devices not limited by transit time effects[1].

A more general goal of this work is to understand ballistic transport in semiconductor nanostructures, which is important in nano-scale HEMTs[2], nano-scale Si MOSFETs[3] several years out on the semiconductor roadmap[4], and research stage structures such as carbon nanotubes[5]. Ballistic transport will be important both in the frequency domain which we investigate here (operational frequency > electron scattering frequency), and the spatial domain (source-drain spacing < mean free path), which we will investigate in future work.

In order to achieve the ballistic limit $\omega\tau_m>1$ at GHz frequencies, we perform our experiments on high-mobility modulation doped GaAs/AlGaAs quantum wells grown by molecular beam epitaxy. The experiments are performed at 4 K. The samples used have a density of $1.1 \times 10^{11}/cm^3$ and mobility of $3.2\ 10^6\ cm^2/V\text{-}s$ at 4 K. After Ni/Ge/Au/Ni/Au (80/270/540/140/2000Å) metallization by electron beam evaporation and rapid annealing at 440 C, we measure the two-terminal microwave impedance from source to drain as a function of frequency. We measure over a dozen samples; the geometry is typically 1 mm x 250 µm. A key point is that this measurement includes the ohmic contact impedance, which varies between < 1 Ω to > 100 Ω. We have carefully quantified the effect of the contact impedance on the microwave impedance.



In order to characterize the impedance of the two dimensional electron gas, we measure both the DC (13 Hz) *and* AC (50 MH to 20 GHz) properties on the same sample. The DC resistance is measured using a lock-in amplifier. The AC impedance is measured by measuring the microwave reflection coefficient S_{11}, and inverting the standard reflection formula $S_{11}= (Z_{load} - 50\ \Omega)/(Z_{load} + 50\ \Omega)$. In our measurement geometry, the sample is mounted at the end of a microstrip line as shown in the figure.

We study two cases: First, where the contact resistance is negligible, and second where it is comparable to the 2DEG impedance. We discuss the former case first.

According to the Drude model, if the contact resistance is negligible, the real part of the impedance is independent of frequency, and the imaginary part of the impedance is inductive, i.e. proportional to frequency[6]. The condition $\omega\tau_m=1$ (and hence the numerical value of τ_m) can be determined from the measured data in this case by reading off the frequency at which Re(Z)=Im(Z). In our experiments this crossover frequency occurs at about 2.2 GHz, implying a value of about 70 ps for τ_m. This value of τ_m so determined is reasonably consistent with the predicted value of 110 ps based on the dc measurement of the mobility on different samples from the same wafer and the relationship $\mu=e\tau/m^*$.

In the second case, where the contact resistance is non-negligible, we find experimentally that the real part of the microwave impedance is equal to the real part of the dc impedance. This impedance includes both the 2DEG impedance and the contact impedance. We conclude from this measurement that, even in the ballistic limit for the 2DEG, the microwave contact impedance is still real, independent of frequency, and equal to the dc measured value. This is the first experimental result on the contact impedance for samples in the ballistic limit ($\omega\tau_m>1$). While this result is not surprising, it cannot be predicted from first principles because the physics of electrical contacts in this limit is not well understood. Thus the value must be determined experimentally, as we have done.

This work lays the foundation for future work on ballistic devices on both the spatial and frequency domain, i.e. device shorter than the mean free path which operate at frequencies higher than the scattering frequency. This is an unexplored but technologically increasingly important regime of device operation.

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[1] M.S. Shur, J.Q. Lu, "Terahertz Sources and Detectors Using Two-Dimensional Electron Fluid in High Electron-Mobility Transistors", *IEEE Transactions on Microwave Theory and Techniques*, v. 48, no. 4, pp. 750-756, April, 2000; J.Q. Lu, M.S. Shur, "Terahertz Detection by High-Electron Mobility Transistor: Enhancement by Drain Bias", *Applied Physics Letters*, vol. 78, no. 17, pp. 2587-2588, April, 2001.
[2] M.S. Shur, "Low Ballistic Mobility in Submicron HEMTs", *IEEE Electron Device Letters*, vol. 23, no. 9, pp. 511-513, September, 2002.
[3] M. Lundstrom, Z. Ren, "Essential Physics of Carrier Transport in Nanoscale MOSFETs", *IEEE Transactions on Electron Devices,* vol. 49, no. 1, pp. 133-141, January, 2002; Y. Naveh, K. Likharev, "Modeling of 10-nm-Scale Ballistic MOSFETs", *IEEE Electron Device Letters*, vol. 21, no. 5, pp. 242-244, May, 2000.
[4] *International Technology Roadmap for Semiconductors*, http://public.itrs.net/
[5] P.J. Burke, "An RF Circuit Model for Carbon Nanotubes", *IEEE Transactions on Nanotechnology*, vol. 2, no. 1, pp. 55-58, March, 2003, and references therein.
[6] P.J. Burke, I.B. Spielman, J.P. Eisenstein, K.W. West, L.N. Pfeiffer, "High Frequency Conductivity of the High Mobility Two-Dimensional Electron Gas", *Applied Physics Letters*, vol. 76, no. 6, pp. 745-747, February, 2000.