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Effect of Nyquist noise on the Nyquist dephasing rate in two-dimensional electron systems

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We measure the effect of externally applied broadband (100 MHz–10 GHz) Nyquist noise on the intrinsic Nyquist dephasing rate of electrons in a two-dimensional electron gas at low temperatures. Within the measurement error, the phase coherence time is unaffected by the externally applied Nyquist noise, including applied noise temperatures of up to 300 K. The amplitude of the applied Nyquist noise is quantitatively determined in the same experiment using a microwave network analyzer.

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The problem of understanding electron-electron interactions in the presence of disorder is a difficult and long-standing issue in modern physics. It is generally believed that electron-electron interactions in disordered systems can be modeled as the interaction between an individual electron and the fluctuating electric field produced by all the other electrons in the system due to its own Johnson/Nyquist noise. Our experiments provide a surprising challenge to this fundamental assumption that has not ever been tested. We test it experimentally by applying Johnson/Nyquist noise from an external circuit, and we find (surprisingly) no affect on the electron-electron interaction rate, measured through weak-localization methods.

Weak-localization measurements use the magnetoresistance of disordered conductors to determine the time scale over which electrons maintain quantum coherence before interacting with their environment. In this paper, we address the question: What is the mechanism of electronic decoherence in disordered two-dimensional (2D) conductors? One mechanism is the so-called Nyquist mechanism of electron-electron interactions involving small energy transfer. This mechanism is believed to be equivalent to the interaction of an electron with the time and space dependent fluctuating electromagnetic fields (i.e., the Nyquist/Johnson noise) produced by all the other electrons in the system,[1] hence the name Nyquist dephasing. If this physical picture is correct, then applying a temporal fluctuating electric field (i.e., Nyquist/Johnson noise) from an external circuit should effect the coherence time measured by weak localization in the same way as the fluctuating electric field produced by the sample itself.[2] We have performed this experiment, and present the results in this paper.

Recent experiments[3] measuring the magnoteresistance of Au metal wires have observed a saturation of the phase-coherence time τ_ϕ as a function of temperature at low temperatures, although not all Au wires seem to show the effect.[4] As a possible explanation for this observation, a proposal[3] that *quantum* fluctuations in the electromagnetic field cause decoherence has generated much theoretical discussion,[5–8] some critical and some supportive. In this paper, we do not directly address the issue of whether quantum fluctuations [which dominate at frequencies above k_BT/h (Ref. 9)] can cause decoherence, but rather whether *thermally* fluctuating electromagnetic fields (which dominate at frequencies below k_BT/h) can cause decoherence. In some sense, the effect of thermally fluctuating electromagnetic fields is a more important and fundamental issue, as much of our understanding[1] of electron-electron interaction in disorded systems is based on the hypothesis that thermally fluctuating electromagnetic fields can cause decoherence, which has not (until now) been directly tested.

In the work critical of the quantum fluctuation hypothesis,[5] it is proposed that external microwave radiation that is not completely shielded from the sample generates electric fields within the sample with sufficient amplitude to cause decoherence, even though they may not be strong enough to cause appreciable heating. An additional, related set of experiments[10–14] has sought to more quantitatively understand the effect of microwave electric fields on the coherence of electrons by intentionally applying a fixed amplitude, monochromatic rf or microwave field. This is typically done by ‘‘irradiating’’ the sample, allowing the leads to act as antennas and transform propagating free space microwaves into local voltages accross the sample. Since the sample size in the experiments is usually much less than the electromagnetic wavelength, the microwave electric field is presumed to be uniform along the length of the sample. Thus, ‘‘irradiating’’ the sample in those experiments is believed to be equivalent to driving a microwave voltage globally accross the complete sample. These experiments, by and large, agree with the calculations in Ref. 2 for the *power* dependence of decoherence due to a monochromatic field, although the exact value of the exponent in the power law is still an open issue.[7] The dependence of the dephasing rate on the *frequency* of the externally applied field, although studied extensively in recent theoretical papers,[5,7] has still not been thoroughly experimentally investigated.

Our experiment can be viewed in some sense as an extension of the experiments discussed above. Instead of applying a fixed amplitude, monochromatic microwave field, we apply a broadband, fluctuating field. Since the fields generated by the electrons in the sample are not fixed amplitude, monochromatic fields, but themselves are broadband and fluctuating, and since it is these fields that are thought to be important for understanding the electron-electron interaction in disordered systems, we argue that it is important to experimentally test the effect of broadband fluctuating electric fields on the quantum coherence of electrons in disordered conductors.

The central result then of this paper is to ask the following question: What is the effect of broadband (100 MHz–10 GHz) thermal fluctuations in the electric field centered

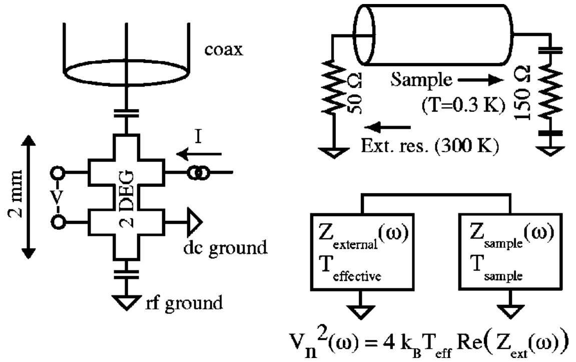

FIG. 1. Schematic of sample geometry and equivalent circuit.

around $\omega \sim \tau_\phi^{-1}$, i.e., $f \sim (2\pi\tau_\phi)^{-1}$, with noise temperature[15] (amplitude) of up to 300 K on the decoherence rate measured by weak localization of electrons in 2D? This amplitude corresponds to a total power of 10 pW.[16] Even though this power level does not cause any observable heating in this or related experiments,[17] we argue below that it should be enough to significantly suppress the coherence, if the modern theory of the equivalence of the electron-electron interaction and scattering off of fluctuating fields is correct.

In the experiments[10–14] that irradiate the sample from free space and allow the leads to act as antennas, it is technically difficult to quantitatively control, model, or even measure the coupling efficiency to the sample, especially over a broad range of frequencies. In our experiment, we use a much more quantifiable (and measurable) coaxial coupling scheme indicated schematically in Fig. 1 and detailed in Ref. 18. We apply the fluctuating voltage globally along the length of the two-dimensional electron-gas (2DEG) sample by terminating the room-temperature end of the coaxial cable shown in the layout in Fig. 1 with a 50-Ω resistor. From the fluctuation-dissipation theorem, the resistor generates a noise voltage with spectral density given by

$$V_n^2 = 4k_B TR, \tag{1}$$

where T is the physical temperature of the external resistor (300 K) and R is the value of the external resistor (50 Ω). The spectrum of these fluctuations[9] is white up to frequencies of order $k_B T/h$.

The sample studied is a GaAs/$Al_xGa_{1-x}As$ modulation-doped heterojunction grown by molecular-beam epitaxy. A hall bar mesa is lithographically defined with four ohmic contacts from diffused Ni/Au/Ge. The sample density and mobility are 1.25×10^{11} cm^{-2} and 600 000 $cm^2/V\,s$, respectively, with a corresponding sheet resistance of roughly 80 Ω/sq. Two additional capacitive contacts are provided to allow for the application of high-frequency fields; these are evaporated Al gates. The gate-2DEG separation is about 5000 Å and the gate area is about 0.25 mm^2, so that the capacitance value is about 50 pF. At frequencies above roughly 100 MHz, the capacitor does not effect the rf voltage. The dc current and voltage leads are several centimeters long gold wires of diameter 50 μm, which act as inductive blocks at frequencies above roughly 100 MHz. The physical temperature of the sample is held at 300 mK for the entire experiment.

In order to determine the amplitude of the applied fluctuating electric field, we consider the effective circuit diagram shown in Fig. 1. We studied this circuit model in detail in another publication,[17] and found it to be valid up to 10 GHz. In this experiment, as in our recent publication, we *measure* the coupling of the sample to the coaxial cable with a microwave network analyzer by measuring the microwave reflection coefficient defined as

$$\Gamma(\omega) = \frac{Z_{sample}(\omega) - 50\ \Omega}{Z_{sample}(\omega) + 50\ \Omega}. \tag{2}$$

We find that the circuit model in Fig. 1 for the sample describes the coupling to the sample (defined as $1-|\Gamma|^2$) to within 20% over almost the entire frequency range considered, with a sample resistance of 150 Ω and capacitance of 50 pF.

Since the resistance of the external resistor has the same value as the characteristic impedance of the coax, it is a standard result from transmission line theory[19] that the effective external impedance "seen" by the sample is $Z_{external}(\omega) = 50\ \Omega$, which is real and frequency independent, even if there is loss in the coax. If the coax is lossless, then the equivalent circuit in Fig. 1 can be used to calculate the noise voltage at the terminals of the sample, with the value of T_{eff} given by the temperature of the external resistor (300 K). The external circuit acts as a noise source with voltage given by the equation in Fig. 1, and a source impedance given by $Z_{external}$. Thus, the amplitude of the voltage fluctuations at the terminals of the sample are

$$\begin{aligned} V_n^2(\omega) &= 4k_B T_{eff} 50\ \Omega \left| \frac{Z_{sample}(\omega)}{50\ \Omega + Z_{sample}(\omega)} \right|^2 \\ &= k_B T_{eff} 50\ \Omega (1 - |\Gamma(\omega)|^2), \end{aligned} \tag{3}$$

where we have inserted the definition of Γ. If there is loss in the coax, then the voltage fluctuations generated by the external resistor will get attenuated, while the coax itself will generate some noise. Mathematically, we lump this effect into a frequency dependent effective temperature for the noise source, so that Eq. (3) is still valid with this redefinition of T_{eff}. We calculate T_{eff} by modeling the loss as uniformly distributed along the length of the coax, and the temperature profile along the coax as linear.

The resultant applied fluctuating voltage determined from the *measured* coupling, the *measured* coax loss, and Eq. (3) are shown in Fig. 2. (The measured coupling and T_{eff} are shown in the insets for reference.) By numerically integrating the spectral density of the voltage fluctuations over the frequency band, we find that the *total* power coupled into the sample is roughly 10 pW. (By comparison, without coax loss and with perfect coupling the coupled power would be $k_B T \Delta B \approx 40$ pW.) Since we *directly measure* the coupling to the sample at each frequency, this power can be considered experimentally determined to within at worst a factor of 2.

The important quantity that determines the change in the quantum phase of an electron[2] is the electric field. In our experiment, the externally applied fluctuating electric field is simply the voltage divided by the sample length (≈ 2 mm). From Fig. 3, we find $E_{ext\ appl} \sim 10^{-7}$V/m/$\sqrt{\text{Hz}}$. The intrinsic

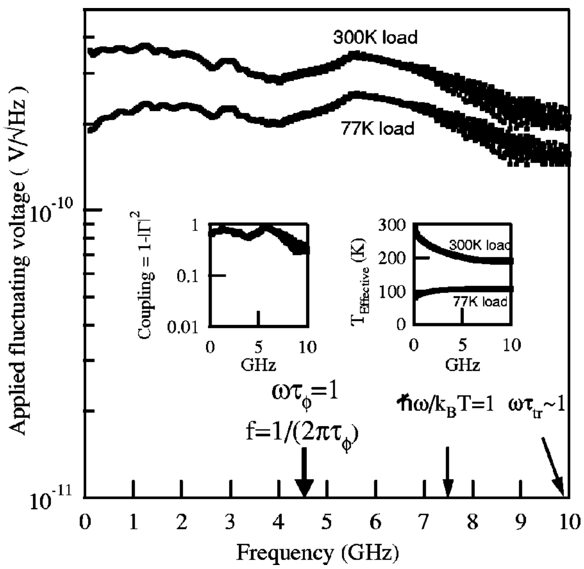

FIG. 2. Applied fluctuating voltage.

fluctuating electric field generated by the sample itself fluctuates on many length scales. For a typical length L we can estimate the typical electric-field strength over that length from Eq. (1) for the voltage over that length (with $R = R_{sq}L/W$), and $E = V/L$: $E^2 \approx 4\ k_B T R_{sq}/(WL) \sim 1/L$. Thus electric fields fluctuating over shorter length scales have higher amplitudes, but it is only those fields that are uniform over at least $L_\phi \equiv \sqrt{D\tau_\phi}$, that cause decoherence.[2] Therefore among the internally generated fluctuating electric fields it is those fields with wave vector $\sim L_\phi^{-1}$, which are most influential in causing decoherence. For the sample studied in our experiment from the above equation we estimate a typical field strength over a length L_ϕ inside the sample of $E_{intrinsic} \sim 10^{-7}\mathrm{V/m/}\sqrt{\mathrm{Hz}}$. In our experiments, then, $E_{ext\ appl} \sim E_{intrinsic}$, from which we conclude that the applied fluctuating field should have sufficient amplitude to effect the coherence time τ_ϕ. The total fluctuating electric-field strength inside the sample will be the sum of the intrinsic and the externally applied fields, added in quadrature due to their fluctuating nature: $E_{total}^2 = E_{intrinsic}^2 + E_{ext\ appl}^2$.

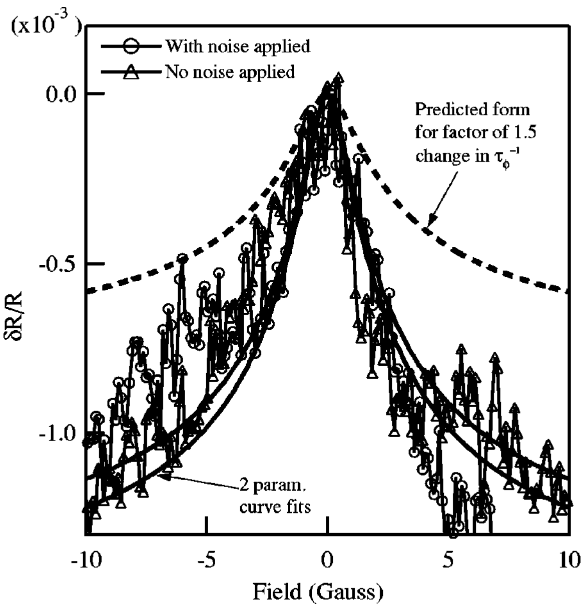

FIG. 3. Weak-localization curve.

Although sample resistances close to 50 Ω allow for good characterization of the microwave coupling, they make measurement of weak localization difficult because of the small resistance changes that must be resolved. Small probe currents must be used to avoid sample heating. For that reason the measured magnetoresistance data is somewhat noisy. We plot in Fig. 3 the measured magnetoresistance for two cases: when a 300-K external resistor is applied and when no external resistor is applied. (The latter was a separate cooldown where the coax connector was disconnected from the sample. The end of the coax was plugged to prevent stray radiation couping to the sample from the end of the coax.) The slight asymmetry is due to mild magnetic properties of the coaxial connector; the magnetoresistance traces measured on the same sample in a different mount with no connector were symmetric.

To determine τ_ϕ, we perform a least-squares fit of the peak to the following functional form:[20–22]

$$\frac{\delta R}{R} = \frac{e^2 R_s}{\pi h}\left[\psi\left(\frac{1}{2}+\frac{H_{tr}}{H}\right)+\frac{1}{2}\psi\left(\frac{1}{2}+\frac{H_\phi}{H}\right) - \frac{3}{2}\psi\left(\frac{1}{2}+\frac{(H_\phi+H_{so})}{H}\right)\right], \tag{4}$$

where H is the applied magnetic field, ψ is the digamma function, and $H_i = \hbar/4eL_i^2$, where i represents the scattering mechanism, and $L_i = \sqrt{D\tau_i}$ the corresponding length. The i's correspond to tr=transport, so=spin orbit, and ϕ=phase breaking. The elastic mean-free path and R_{sq} are related, so that there are effectively three free parameters in the theory curve. In performing a two-parameter fit (holding τ_{so} fixed), we find the fit results of τ_ϕ and τ_{tr} to be independent of the spin-orbit scattering time, as long as τ_{so} is sufficiently larger than τ_ϕ and τ_{tr}. This is consistent with the results of Dresselhaus,[21] who studied the spin-orbit scattering rates in GaAs 2DEG's in detail. In Fig. 3, we plot the fitted results for a two-parameter fit, keeping H_{so} fixed at 0.013 G, the value predicted by the Dresselhaus data for our density. We find a value of 34 ps and 37 ps for τ_ϕ in the presence and absence of the externally applied Nyquist noise, respectively.[23] (We find a value of 13 ps for τ_{tr} in both cases, in reasonable agreement with that value of 22 ps calculated from the measured value of R_{sq}.) The value of τ_ϕ cannot be said to have changed within the measurement error.

From the data shown in Fig. 3 we can estimate that τ_ϕ^{-1} changed by no more than 50%. To illustrate this point, we plot the predicted curve for a factor of 1.5 change (increase) in τ_ϕ^{-1}; this change is clearly ruled out by the experiment. The same conclusion applies if we perform a three-parameter fit (varying τ_{so}, τ_ϕ, and τ_{tr}) or a one-parameter fit (varying only τ_ϕ and using estimated values for τ_{tr} and τ_{so}). Thus, the experimental conclusion is robust and independent of the particular curve-fitting procedure used. We measure the magnetoresistance when the physical temperature of the external resistor is changed from 300 K to 77 K, and find a similar lack of change in τ_ϕ with the change in applied noise voltages. To an experimental resolution of 0.1 e^2/h, we also find no change in the $B=0$ conductance under these changes in externally applied noise.

We know of only one rigorous, testable calculation[24] of the effect of broadband externally applied noise on coherence, which seems to predict that in the presence of external circuit noise with noise temperature T_0,[15] and with good circuit coupling as we have in this experiment, the measured τ_ϕ should be comparable to the value that one would measure in the absence of such noise if the physical temperature of the electrons was equal to T_0. For the experiment considered here, that would imply that our measured value of τ_ϕ in the presence of 300 K of noise should be essentially zero, fully suppressing the weak-localization peak, in contradiction to what we observe. However, that calculation assumes good coupling all the way up to frequencies of order $k_B T_0/h$. In our experiment, that is many tetrahertz, and we do not have good coupling all the way up to that frequency.

In conclusion, we have not observed any change in τ_ϕ under the application of broadband, fluctuating fields with an amplitude which, according to our own arguments and those of Refs. 1,2,24, should be enough to significantly suppress the coherence time, if the hypothesis that the electron-electron interaction in disordered systems is equivalent to the interaction of a single electron with broadband, fluctuating electric fields is correct. At present the reason for this discrepancy is unknown. One possibility is that the hypothesis is in some way flawed. Another possibility is that, in our experiments, the electron motion is not entirely diffusive in the frequency range around $\omega \sim \tau_\phi^{-1}$, which has always been assumed in calculations of τ_ϕ. In other experiments on similar samples,[17] we found the motion to be ballistic at frequencies higher than τ_{tr}^{-1}, which is in the 10-GHz range for the samples measured here. More calculations are needed to investigate this unexplored regime where $\tau_\phi \sim \tau_{tr}$.

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[15] The noise temperature is a standard measure of the amplitude of voltage fluctuations, defined such that the spectral density of voltage fluctuations corresponding to a noise temperature T is given by $k_B TR$, with R equal to 50 Ω.

[16] We were able to completely suppress the weak-localization peak, i.e., the phase coherence, with high power, fixed amplitude, monochromatic fields, as other groups have done (Refs. 10–14). We did these experiments at multiple frequencies between 50 MHz and 20 GHz, at fixed power levels. However, since the spin-orbit coupling in our experiments is weak (in contrast to the experiments of Refs. 10–12), the effect of rf induced decoherence and simple Joule heating have the same experimental signature, and we have not been able to clearly separate the two effects.

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[22] Strictly speaking, Eq. (6) is valid only at fields smaller than H_{tr}, which for the sample measured here is ~ 1 G. We assume this curve holds semiquantitatively for larger values of H in order to get a semiquantitative estimate of τ_ϕ.

[23] Our measured values for τ_ϕ are comparable to those measured in GaAs 2DEG's in K.K. Choi, D.C. Tsui, and K. Alavi, Phys. Rev. B **36**, 7751 (1987), even though the mobility in this sample is higher.

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