Studies of $h/e$ Aharonov-Bohm Photovoltaic Oscillations in Mesoscopic Au Rings

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We have investigated a mesoscopic photovoltaic (PV) effect in micron-size Au rings in which a dc voltage $V_{dc}$ is generated in response to microwave radiation. The effect is due to the lack of inversion symmetry in a disordered system. Aharonov-Bohm PV oscillations with flux period $h/e$ have been observed at low microwave intensities for temperatures ranging from 1.4 to 13 K. For moderate microwave intensities the $h/e$ PV oscillations are completely quenched providing evidence that the microwaves act to randomize the phase of the electrons. Studies of the temperature dependence of $V_{dc}$ also provide evidence of the dephasing nature of the microwave field. A complete theoretical explanation of the observed behavior seems to require a theory for the PV effect in a ring geometry.

I. INTRODUCTION

Studies of the transport properties of disordered mesoscopic systems have revealed a number of interesting quantum interference phenomena. These effects include the observation of Aharonov-Bohm or $h/e$ conductance oscillations in micron-size Au rings, universal (or aperiodic) conductance fluctuations (UCF) in small wires, and the time-dependent conductance fluctuations due to the motion of even a single defect or impurity. In each case, the conductance exhibits fluctuations of order $e^2/h$, provided the electron retains phase coherence over the length of the system. Central to the observation of such interference phenomena is the fact that an electron scattered coherently off the random impurity configuration over a distance, $L_d$, defined as the phase coherence length. Another consequence of coherent impurity scattering is that a disordered mesoscopic system lacks a center of inversion symmetry which allows for non-linear effects that would otherwise be forbidden.

One such non-linear response concerns a mesoscopic photovoltaic (PV) effect in which a dc-voltage, $V_{dc}$, is generated in response to microwave radiation, even with no current applied from external leads. The PV effect has much in common with UCF and consequently $V_{dc}$ is sensitive to small changes in the impurity distribution and magnetic field, $H$. Initial PV experiments centered on studies of small microbridges where $V_{dc}$ was shown to exhibit aperiodic fluctuations as a function of $H$ at low temperatures ($\sim 4$ K). More recent studies of the PV effect in submicron-size rings clearly revealed Aharonov-Bohm PV oscillations of flux period $h/e$, in addition to the aperiodic conductance fluctuations. One surprising feature of these results was that the PV signal was quite pronounced, even for temperatures at which the analogous conductance fluctuations were minute and difficult to observe. The robust nature of these results demonstrates that the mesoscopic PV effect also promises to be a powerful and convenient probe of mesoscopic systems and may lead the way for possible microwave device applications.

In this paper we report detailed studies of the PV effect as a function of magnetic field, microwave power, and temperature in submicron-diameter Au rings. Studies of $V_{dc}$ as a function of the microwave power show that the $h/e$ PV oscillations are quenched in response to a moderate amount of microwave radiation. Our data suggests that the microwave period plays a fundamental role in determining the temperature dependence of the PV response when it is of order the phase coherence time, $\tau_\varphi$. Although a complete analysis of our results awaits an extension of the PV theory to include the case of a ring geometry, our data provides evidence of the dephasing nature of a high-frequency field in a mesoscopic system.

II. THEORY OF THE MESOSCOPIC PHOTOVOLTAIC EFFECT

A. The Mesoscopic Photovoltaic Effect At Zero Temperature

The calculation of Fal’ko and Khmel’nitskii for the magnitude of the PV effect considers the case of a metallic mesoscopic wire or microbridge illuminated by high-frequency (microwave) radiation. A conductor in the presence of a high frequency field $E_{ac}$ will absorb

$$N_e = \frac{E_{ac}^2 L^2 G}{h\omega}$$

photons per unit time, where $G$ is the conductance, $L$ is the sample length (where $L \leq L_d$), and $h\omega$ is the photon energy. In the weak-field limit (i.e., $eE_{ac}L/h\omega \ll 1$), an electron will absorb at most one photon, and $N_e$ equals the number of electrons that are excited into empty states above the Fermi energy, $E_F$. If the scattering potential of the electron is perfectly symmetric then half the carriers will diffuse to the left voltage probe and half to the
right. In this case the net photovoltage would be zero. However, due to the asymmetry of the random impurity potential, a different number of electrons diffuse to opposing voltage contacts. The degree of asymmetry $\alpha$ in a disordered mesoscopic junction was estimated by the theory \cite{2} as the ratio of the magnitude of the UCF to the sample conductance: $\alpha \sim e^2/hG$. Putting these effects together, the net dc voltage $V_{dc}$ induced by the microwaves is given by $V_{dc} \sim (eN_{\alpha}R)\tau_f$, where $R$ is the sample resistance. In the low-frequency limit ($\omega\tau_f \ll 1$) the relevant time scale of the system is determined by $\tau_f$, the time it takes the electron to diffuse to the voltage contacts, not the period ($\sim \omega^{-1}$) of the microwave field. In this case, $\tau_f$ is substituted for $\omega^{-1}$ in Eq. 1 and the magnitude of the net microwave induced dc voltage is given by

$$V_{dc} \approx \frac{e}{\tau_f} R \left( \frac{eE_{ac}L\tau_f}{\pi^2h} \right)^2 \left[ \frac{\lambda V_d}{L^2} \right]^{1/2}, \quad \omega\tau_f \ll 1. \quad (2)$$

The numerical factors $\lambda$, $V_d$, and $\tau_f$ depend on the sample dimensionality $d$ (see Table 1 in Ref. 2). Note that $V_{dc}$ in Eq. 2 is the rms voltage averaged over different realizations of the random potential.

The deep connection between the PV effect and UCF hinges on the fact that the degree of asymmetry is related to the electron’s transmission probability across the sample. As a result, the magnitude and polarity of the PV effect as it does not include the adverse averaging that the PV effect as it does not include the adverse averaging due to photon energy averaging (where $\omega\tau_f \ll 1$). For a typical metallic mesoscopic sample, the degree of asymmetry is small ($\alpha \sim 10^{-3}$) and $V_{dc}$ is on the order of 1 nV at a frequency of 10 GHz for $E_{ac} = 1$ V/m and $R = 10$ $\Omega$. Note that the PV effect is entirely mesoscopic in origin and there is no inherent macroscopic or background component as in the case of the UCF. In a disordered macroscopic system (i.e., $L_0 \ll L$) the PV effect is negligibly small since currents from individual phase-coherent regions are random in sign and add incoherently.

### B. The Mesoscopic Photo voltaic Effect in the High-Frequency and High-Power Limits

The microwave field can act to randomize the phase of the electron at sufficiently high powers. Previous theoretical and experimental \cite{14,12} studies have centered on the dephasing effects of microwaves on the weak localization magnetoresistance. The experiments are complicated by electron heating effects, which can also be important at high power levels \cite{13}. Nevertheless, phase breaking due to the “dynamical” influence of microwaves (apart from heating) has been observed \cite{14,12}. The dephasing effects of a microwave field on the $h/e$ oscillations in a mesoscopic system have yet to be studied. In related work \cite{14}, the effect of a finite measurement frequency (from 250 to 1.2 GHz) on the magnetic conductance of submicron-diameter Ag rings has been studied, although no suppression of the $h/e$ conductance amplitude was observed. As we will discuss below, it is possible to study the dephasing effects of a microwave field through a detailed analysis of the microwave power and temperature dependence of the $h/e$ PV oscillations in samples with a ring geometry.

The microwave power and temperature dependence of $V_{dc}$ depends critically on the interplay between the relative magnitudes of the strength ($E_{ac}$) and frequency ($\omega$) of the microwaves, and the mesoscopic scales of time ($\tau_0$ and $\tau_f$) and energy ($E_c$) discussed above. The theory \cite{3} calculates the magnitude of the PV effect in the various asymptotic regimes of the irradiating field parameters. In the low-power high-frequency limit (i.e., $h\omega > E_c$ and $\omega^{-1} < \tau_f$), $V_{dc}$ is reduced in magnitude by a factor of $n^{-1/2}$ due to photon energy averaging (where $n = h\omega/E_c$). Eq. 2 is also modified by the substitution $\tau_f \rightarrow \omega^{-1}$ and $V_{dc}$ is given by

$$V_{AF} \approx eR \left( \frac{\omega}{\tau_f} \right)^2 \left( \frac{eE_{ac}L}{h\omega} \right)^2 \left[ \frac{\lambda V_d}{L^2} \right]^{1/2}, \quad \omega\tau_f \gg 1. \quad (3)$$

Note that in the high-frequency limit $V_{dc}$ is strongly frequency dependent, in comparison to Eq. 2 which is independent of frequency.

In the limit of strong microwave fields the electron may absorb more than one photon in time $\tau_f$ which leads to energy and phase relaxation of the carriers \cite{3}. The number of photons $\xi^2$ absorbed by a particular electron during a diffusion time $\tau_f$ is given by

$$\xi^2 = \frac{N_{\alpha}\tau_f}{N} = \left( \frac{eE_{ac}L}{h\omega} \right)^2,$$ 

(4)
where \( N_e \) is defined by Eq. 1, \( N = (dN/dE)\hbar \omega \) is the total number of electrons within \( \hbar \omega \) of the Fermi energy, and the conductance \( \sigma \) is defined by \( \sigma V_d = e^2 D(dN/dE) = GL^2 \) (where \( D \) is the diffusion constant). Assuming the electron absorbs at least one additional photon before exiting the sample (i.e., \( \xi^2 = 1 \)), a microwave-enhanced phase relaxation time \( \tau_{ac} \) can easily be determined from Eq. 4,

\[
\tau_{ac} = \frac{N}{N_e} = \frac{(\hbar \omega)^2}{(eE_{ac})^2D}. \tag{5}
\]

The length scale over which the microwaves randomize the electron’s phase is defined by \( L_{ac} = (D\tau_{ac})^{1/2} = \hbar \omega/eE_{ac} \). Although the connection was not made explicit by the PV theory, \( \tau_{ac} \) has been studied in connection with the dephasing effects of a microwave field on the weak localization magnetoresistance.

For strong microwave fields (\( \xi \gg 1 \)) the theory predicts that the linear power dependence of \( V_{AF} \) in Eqs. 2 and 3 will saturate due to energy and phase relaxation of the carriers. As a result, the quadratic field dependence is replaced by a much weaker logarithmic dependence. \( V_{dc} \) in the high-power-high-frequency limit is given by

\[
V_{AF} \approx \sqrt{20eR} \left( \frac{\omega}{\tau_f} \right)^{1/2} \ln(\xi), \quad \omega \tau_f \gg 1, \tag{6}
\]

where \( L \gg L_{ac}, w, t \) for a 1D sample of width \( w \) and thickness \( t \). The logarithmic power dependence results from a competition between the dephasing effect of the microwaves and the growth of the number of microwave generated carriers \( N_e \) with increasing power. Therefore, the effects of a microwave-enhanced phase relaxation time \( \tau_{ac} \) will be apparent in measurements of \( V_{dc} \) over a wide range of microwave powers.

**C. The Effect of Partial Phase Coherence and Thermal Energy Averaging**

For high temperatures, \( L_\phi \) can be smaller than \( L \), and \( V_{dc} \) decreases with increasing temperature due to the averaging of \( n = L / L_\phi \) phase coherent subsystems. Quantitative estimates for \( V_{AF} \) as a function of temperature follow naturally from Eqs. 2, 3, and 4 using the substitution \( L \rightarrow L_\phi, \tau_f \rightarrow \tau_\phi \), and the relation \( \tau_\phi \rightarrow L_\phi^2/D \). The temperature dependence in the high-power-high-frequency regime is given from Eq. 4,

\[
V_{AF}(T) \sim \sqrt{20eR} \left( \frac{\omega}{\tau_f} \right)^{1/2} \ln[\xi(T)], \tag{7}
\]

where the parameter \( \xi(T) = eE_{ac}L_\phi/\hbar \omega \) varies with temperature \( 1 \) since \( 1 \sim T^{-p/2} \) (where \( p = 3/2 \) depending on the phase relaxation mechanism and the sample dimensionality). The precise temperature dependence depends on the relative value of \( \tau_\phi \) and \( \omega^{-1} \).

For temperatures greater than around 5 K, \( \tau_\phi \) can become less than \( \omega^{-1} \), and the temperature dependence becomes much stronger due to the substitution \( \omega^{-1} \rightarrow \tau_\phi \). We would therefore expect \( V_{AF} \) to vary logarithmically with temperature. The parameter \( \xi \) can become less than unity at relatively high temperatures and the difference between the strong and weak fields is eliminated. Physically this crossover occurs because \( \tau_\phi \) becomes less than \( \tau_{ac} \), and the phase of the electron has been randomized before it has time to absorb additional photons. In this case the temperature dependence of \( V_{AF} \) is reduced to that expected for “low” microwave powers.

In the low-power limit, the temperature dependence of \( V_{AF} \) also depends on the relative value of \( \tau_\phi \) and \( \omega^{-1} \). In the high-frequency limit (\( \omega^{-1} < \tau_\phi < \tau_f \)) the temperature dependence of \( V_{AF} \) (in 1D) is obtained from Eq. 4 (again substituting \( L \rightarrow L_\phi \) and \( \tau_f \rightarrow \tau_\phi \))

\[
V_{AF}(T) \propto \tau_\phi^{-1/2} L_\phi^{-2d/2} \propto T^{-p/4}, \quad \omega \tau_\phi \gg 1. \tag{8}
\]

As the temperature is increased further the condition \( \tau_\phi < \omega^{-1} < \tau_f \) holds and the temperature dependence of \( V_{AF} \) in the ”low-frequency” limit (see Eq. 3) is given (in 1D) by

\[
V_{AF}(T) \propto \tau_\phi L_\phi^{-2d/2} \propto T^{-p/4}, \quad \omega \tau_\phi \ll 1. \tag{9}
\]

In this low-frequency limit \( V_{dc} \) is expected to be a strong function of temperature in contrast to the high-frequency limit. Therefore, studies of \( V_{dc} \) over a wide temperature range may not scale according to a single power law and may reveal evidence that the time scale of the microwaves (\( \omega^{-1} \)) has a strong influence on the behavior of a mesoscopic system.

Analogous to UCF, thermal averaging of \( nT = k_B T/E_c \) uncorrelated energy intervals leads to a \( T^{-1/2} \) reduction in magnitude of \( V_{AF} \), at low powers. However, for \( \hbar \omega > E_c \), the photon energy supersedes the correlation energy and the number of uncorrelated electron intervals is given by \( k_B T/\hbar \omega \). For even larger photon energies (i.e., \( \hbar \omega > k_B T \)) thermal smearing is circumvented altogether and \( n_T = 1 \). Thermal averaging can introduce a second important length scale \( L_T = \sqrt{hD/k_B T} \), or the thermal length, defined as the distance electrons differing in energy by \( k_B T \) diffuse before their wavefunctions are significantly out of phase. At high temperatures it is possible for \( L_T \) to become smaller than \( L_\phi \), where the fundamental mesoscopic length scale is determined by the smaller of the two.

**D. The Photovoltaic Effect for Ring Samples**

The PV theory by Fal’ko and Khmel’nitskii, as discussed above, estimates the magnitude of the aperiodic PV fluctuations, \( V_{AF} \), for the case of a microjunction geometry. The theory has not yet been extended to include the \( h/e \) PV oscillations, \( V_{h/e} \), observed in samples
with ring geometries \[1,2\]. In the low-frequency low-field limit we would expect the magnitude of the aperiodic and \(h/e\) PV oscillations to have similar power dependences. However, it is well known from the UCF studies \[3\] that the \(h/e\) conductance oscillations are suppressed more strongly by inelastic scattering than are the aperiodic fluctuations. The \(h/e\) PV oscillations are more sensitive to inelastic scattering since the electron must traverse the entire circumference of the ring without having its phase randomized. In contrast, the aperiodic fluctuations can result from relatively small paths confined to the linewidth of the ring. As a result, the \(h/e\) oscillations are suppressed exponentially according to a phase coherence survival probability, \(\exp(-\pi r/L_\phi)\), for \(L_\phi < \pi r\), where \(r\) is the radius of the ring \[3\]. In the case of the PV effect, we expect the dephasing due to the microwave field to cause \(V_{h/e}\) and \(V_{AF}\) to scale quite differently as a function of microwave power. In the absence of a quantitative theory, we predict that the power and temperature dependence of the \(h/e\) PV oscillations is approximately given by

\[
V_{h/e}\sim E_{ac}^2 \exp(-\pi r/L_{\text{eff}}),
\]

where \(L_{\text{eff}} \approx \left[1/L_\phi^2 + 1/L_{ac}^2\right]^{-1/2}\) is the effective phase coherence length. In Eq. \(10\) we see that \(V_{h/e}\) scales quadratically with the microwave field at low powers (where \(L_{\text{eff}} \approx L_\phi\)). As \(L_{ac}\) becomes less than \(L_\phi\), due to excessive electron-photon scattering, the exponential suppression will dominate the square-law dependence. Therefore, a detailed experimental study of the power dependence of the PV effect in submicron-size rings should provide clear evidence of the dephasing effects of a microwave field in a mesoscopic system.

### III. EXPERIMENTAL SETUP

The samples used in this study consisted of four submicron-diameter Au rings fabricated using a scanning electron microscope converted for electron beam lithography \[13\]. Although similar results were found for all four rings, the data to be shown below pertain to only two of the samples. Ring \#1 had an inner diameter of \(d \approx 3300\ \text{Å}\) and linewidth \(w \approx 550\ \text{Å}\), and for ring \#2 \(d \approx 4700\ \text{Å}\) and \(w \approx 700\ \text{Å}\). Both rings were 200 Å thick. The sample dimensions were determined to within 10% using the scanning electron microscope. Narrow voltage probes, with the same linewidth as the ring, extended outwards 0.5 μm on opposite sides of the ring before widening to 8 μm. Therefore the wide voltage contacts were separated in length, \(L\), by 1 μm. We note that such wide voltage contacts may act as antennas tending to strongly couple the sample and the microwave radiation. The samples are effectively one-dimensional since \(L \gg w\). Based on the total sample resistance of 30 Ω, and the number of squares (~15), the sheet resistance was estimated as \(\approx 2.0\ \Omega\) at \(T = 4.2\ \text{K}\). The diffusion constant was estimated from resistivity measurements to be \(D \approx 100\ \text{cm}^2/\text{s}\).

For all the PV data to be shown in this paper the microwave frequency was 8.4 GHz corresponding to a microwave energy of \(\hbar \omega \approx 35\ \mu\text{eV}\). This is smaller than the thermal spread in energies \(k_BT = 120\ \mu\text{eV}\) for our lowest measurement temperature, 1.4 K, where \(k_BT/\hbar \omega \approx 3.5\). For typical disordered metallic samples \[4\], like the ones used in this study, \(L_\phi \approx 1\ \mu\text{m}\) at 1 K and \(D \sim 100\ \text{cm}^2/\text{s}\). Accordingly, \(E_c\) is usually of order 10 μeV yielding a correlation temperature of \(E_c/k_B = 0.1\ \text{K}\). For the temperatures used in this work, it is likely that the condition \(E_c < \hbar \omega < k_BT\) holds and \(V_{dc}\) should be affected by thermal smearing. Given these numbers, \(\omega \tau_\phi \sim 5\) for 10 GHz radiation, and Eq. \(8\) should pertain to the high-frequency regime for temperatures around 1 K.

The samples were mounted in a microwave cavity which had a resonant frequency of 8.4 GHz for its TE 210 mode \[13\]. They were located at a maximum of the electric field, with this field directed in the plane of the film. The cavity was inside a vacuum can which was usually filled with liquid He to minimize Joule heating of the sample by the microwave field. This was all positioned inside a superconducting solenoid which provided a magnetic field perpendicular to the plane of the film. The microwave field was modulated at 150 Hz, and the sample voltage was measured with a lock-in amplifier using a transformer coupled preamplifier. This scheme allowed us to conveniently measure the very small signals which were encountered in the mesoscopic PV effect. We will refer to the voltage measured in this way as \(V_{dc}\) even though it was not a strictly dc measurement.

In order to compare the measured value of \(V_{dc}\) with the theory, the magnitude of the microwave field was calibrated using the procedure discussed previously \[12\]. The maximum output power of the microwave generator was 1 mW, however, the maximum input power to the microwave cavity was of order 0.25 mW due to attenuation in the coaxial cable leading down the cryostat. By changing the frequency of the microwaves (for fixed input power) a resonant peak in \(V_{dc}\) was observed which could then be used to estimate the \(Q\) of the cavity. The microwave field \(E_{ac}\) was then calculated using an estimated \(Q\) value of 25 for the maximum microwave power.

The absolute magnitude of the microwave field could be in error by as much as a factor of five due to possible inaccuracies in estimations of the attenuation and the \(Q\) value. However, the relative magnitude of the power (field) was accurately determined from the attenuation setting on the microwave power supply. The maximum attenuation of the input power (0.25 mW) from the microwave generator, for which \(V_{dc}\) was just indistinguishable from the instrumental noise, was -57 dB. The lowest power setting for a discernible PV signal was -52 dB. For the measured power dependence of \(V_{dc}\) to be discussed below, the power (field) settings ranged from -52 dB (\(E_{ac} \approx 0.12\ \text{V/m}\)) to -10 dB (\(E_{ac} \approx 16\ \text{V/m}\)).
IV. MEASUREMENTS OF THE PHOTOVOLTAIC EFFECT IN AU RINGS

A. Typical Results and Data Presentation

In Fig. 1(a) we show typical results for the magnetic field dependence of the PV effect for ring #1 at T = 4.2 K. $V_{dc}$ was quite reproducible and constituted a true ‘magnetofingerprint’ where the solid (dotted) line shows data for which the magnetic field was increasing (decreasing) in magnitude. As expected, the data clearly reveal both the $h/e$ PV oscillation ($V_{AF}$) and the aperiodic fluctuations ($V_{AF}$). Based on the known geometry of the ring, the period of the $h/e$ oscillations was expected to be $\sim 350$ Oe. This is in agreement with the observed period of approximately 300 Oe which can be obtained by inspection of Fig. 1(a) where we see roughly 3.5 oscillations over the field range 3000 to 4000 Oe. The aperiodic correlation field, $H_c(\sim \Phi_o/L_{\phi}w) \approx 2500$ Gauss, can also be determined by inspection of Fig. 1(a), where we see two aperiodic fluctuations spaced over an approximate field range of 5000 Oe. From the measured linewidth of the ring $w = 550$ Å, the phase coherence length can be estimated as $L_{\phi} \approx 0.3$ μm, which is roughly consistent with previous results for similar samples and temperatures. The aperiodic and $h/e$ PV oscillations are also easily observed in a Fourier transform (FT) of the raw data as can be seen in Fig. 1(b). The $h/e$ frequency range was 0.0025-0.0045 Oe$^{-1}$ which corresponds to a field range of 220-400 Oe. The $h/e$ peak in the FT is centered about 0.0035 Oe$^{-1}$ (or 285 Oe) which agrees with the value obtained by inspection above.

We note however that the $h/2e$ oscillations were conspicuously absent from the data and were not discernible from the Fourier transforms. This was surprising given the robust size of the $h/e$ oscillations. However, in analogy with the UCF, the $h/2e$ oscillations are expected to be exponentially suppressed in comparison to the $h/e$ oscillations. Furthermore, the dephasing effects of the microwave field would further decrease the amplitude of the $h/2e$ oscillations, relative to the $h/e$ oscillations, a fact which may explain their absence.

In order to compare with the theory (Eqs. 1-2), the rms value of the PV fluctuations were computed. The $h/e$ PV oscillations and aperiodic PV fluctuations were separated by computing the inverse FT after selecting a region surrounding one of the peaks in the FT. The data after filtering is shown in Fig. 1(c) where we see that the frequency components are clearly separated. The rms values of the $h/e$ oscillations ($V_{h/e}$) and aperiodic fluctuations ($V_{AF}$) were then easily computed over a fixed magnetic field range to compare with the theory.

B. Power Dependence of the Photovoltaic Effect

Before making a quantitative comparison of the power (field) dependence of $V_{dc}$ with the theory it is instructive to first consider several qualitative features of the data. In Fig. 2(a) we show $V_{dc}$ for ring #2 at 1.4 K for microwave power levels differing by roughly a factor of 1000. For the moderate microwave field ($E_{ac} \approx 0.6$ V/m), $V_{dc}$ exhibited $h/e$ oscillations superimposed upon the slowly varying aperiodic fluctuations. For the larger microwave field ($E_{ac} \approx 16$ V/m) it is seen that the magnitude of the aperiodic fluctuations clearly increased, however, the $h/e$ oscillations were quenched and not distinguishable above the noise. At somewhat lower microwave levels ($E_{ac} \approx 0.12$ V/m), as in Fig. 2(b), the aperiodic PV fluctuations were roughly the same size as the $h/e$ oscillations. (Note the change in the voltage scale between Figs. 2(a) and (b).) For still lower microwave levels the PV effect was difficult to distinguish above the noise.

Several semi-quantitative features of this data are clearly evident. First, it is obvious that we are not in any type of linear response regime. An increase in microwave power by a factor of 10,000 only resulted in an increase in $V_{AF}$ by roughly a factor of 35. This can be seen by comparing Fig. 2(b), where $V_{AF}(0.12 \; V/m) \sim 1$ nV, and Fig. 2(a) where $V_{AF}(16 \; V/m) \sim 35$ nV. This weak power dependence was to be expected from the logarithmic power dependence predicted by the theory (see Eq. 1). The power dependence of the $h/e$ oscillations clearly shows that large microwave powers are causing dephasing since $V_{h/e} \approx 0$. The dephasing effects of the microwaves were also evident through changes in the aperiodic correlation field ($H_c \sim \Phi_o/L_{\phi}w$, where $\Phi_o$ is the flux quantum). In Fig. 2(a) this is clearly demonstrated where $H_c$ is seen to increase by nearly a factor of seven as $E_{ac}$ is changed by a factor of 30. The increase in the correlation field at high microwave powers was not discussed explicitly by the theory, although it is likely due to a decrease in $L_{\phi}$ resulting from the dephasing nature of the microwaves.

The results of a quantitative study of the power dependence of the PV effect at 1.4 K are shown in Fig. 2(c). Each data point represents the rms value of $V_{dc}$ computed over a magnetic field sweep from 0 to 8000 Oe. Fig. 2(c) contains data shown previously in Figs. 2(a) and (b), and for four other microwave field values. One aspect of these measurements that will limit a precise comparison with the theory centers on the relatively small number of aperiodic fluctuations observed over the available magnetic field range. Furthermore, more data could have been taken in smaller increments of the microwave field. The basic power dependence of the aperiodic PV fluctuations is clear however, where from Fig. 2(c) it can be seen that $V_{AF}$ (solid squares) grows with the microwave field before saturating at high fields. In contrast $V_{h/e}$ grows more slowly with the microwave field before becoming completely quenched for fields above about 8 V/m.
In Fig. 3(c) we show the results of a fit (solid line) to the logarithmic power dependence predicted for the aperiodic fluctuations, $V_{AF} \sim b \ln(a E_{ac})$, as estimated by the theory (see Eq. 3). The parameters $a = 6.6$ and $b = 2.1$ were determined from the fit. The data is in agreement with a logarithmic power dependence over a wide range of microwave field strengths. Although we do not show the results of the fits here, both $V_{AF}$ and $V_{h/e}$ were consistent with a quadratic field dependence (as expected in the linear response regime for $E_{ac} < 1$ V/m. From Fig. 3(c) we see that the transition between the linear response and the high-power regime occurs for microwave fields above 1 V/m. The theory predicts that this transition should take place when the number of photons absorbed (emitted) by the electron in time $\tau_\phi$ is greater than one [i.e., $\xi = eE_{ac}L/h\omega > 1$]. Based on the microwave energy (35 $\mu$eV) and sample length ($L \sim 1 \mu$m) the theory predicts a crossover for $E_{ac} \sim 35$ V/m. Given this, a fit parameter of $a = eL/h\omega \approx 1/35$, not 6.6, should have been obtained from the data. This discrepancy is hard to reconcile with the data unless we have underestimated the magnitude of the microwave field by at least an order of magnitude, or the power absorbed by the sample by a factor of 1000. From the observed power dependence of the aperiodic fluctuations it is apparent that we are at least in agreement the logarithmic power dependence predicted by the theory.

It is clear from Fig. 3(c) that the power dependence of the $h/e$ oscillations (triangles) is quite different from the aperiodic fluctuations for microwave fields greater than 1 V/m. For microwave fields greater than roughly 8 V/m, the $h/e$ oscillations are completely quenched in contrast to the aperiodic fluctuations. This behavior was expected from Eq. 10, where it was anticipated that the dephasing nature of the microwaves might give rise to an exponential suppression at high powers. In Fig. 3(c) the solid line results from a fit to following expression $V_{h/e} \approx bE_{ac}^2 \exp(\pi\tau_\phi/L_{\text{eff}})$, where $L_{\text{eff}} \approx [1/L_\phi^2 + 1/L_{ac}^2]^{-1/2}$ and $L_{ac} \approx aE_{ac}$, as expected from Eq. 11. It was also assumed that $\pi\tau_\phi \approx L_\phi$ which is a reasonable approximation at 1.4 K. We see that there is good agreement with Eq. 10, although measurements at more values of $E_{ac}$ are needed for a more stringent comparison.

C. Temperature Dependence of the PV Effect

Fig. 3(a) shows raw PV data at two temperatures for ring #2 ($d = 4700$ Å and $w = 700$ Å), for the “moderate” microwave field ($E_{ac} \approx 0.6$ V/m) as shown in Fig. 2(a). As expected, the magnitude of both the aperiodic and $h/e$ PV oscillations decreased as the temperature was increased. In Fig. 3(b) we take a closer look at data obtained at $T = 11$ K. The Aharonov-Bohm oscillations were visible but were much smaller in comparison to the results obtained at $T = 1.4$ K. That the $h/e$ PV oscillations persisted to such high temperatures was surprising, since the analogous $h/e$ conductance oscillations are usually difficult to detect at these temperatures ($> 5$ K) for similar samples.

In Fig. 3(c) we have plotted the rms values of both the aperiodic $V_{AF}$ and $h/e$ oscillations $V_{h/e}$ for the raw data shown in (a) and (b), and five other temperatures ranging from $T = 1.4$ to 14 K. The rms values were computed in the same manner as discussed in connection with Fig. 3(c). From the theory (see Eqs. 10) we would expect $V_{AF}$ to decrease logarithmically as a function of temperature in the high-power regime and according to a power-law ($V_{AF} \sim T^{-p_1}$) in the low-power regime. In the low-frequency limit, $p_1 = 7/4p + 1/2$, while in the low-power high-frequency regime the temperature dependence is much weaker ($p_1 = p/4 + 1/2$), where the factor of 1/2 is due to thermal smearing. In Fig. 3(c) we show the result of a fit (solid line) to a logarithmic temperature dependence of the form $V_{AF} \sim a \ln(b/T)$ (see Eq. 3). The fit yields reasonable agreement for low temperatures ($< 4.2$ K) although there is some deviation from the logarithmic dependence at higher temperatures. Given the scatter in the data, it is not entirely clear whether this deviation warrants a quantitative explanation. However, assuming the deviation is real, the fact that the magnitude of the microwave field, 0.6 V/m, is at the transition between the low and high-power regimes offers a possible explanation. In the high-power regime there are multiple electron-photon interactions (i.e., $\xi > 1$) and $L_{ac} < L_\phi$. As the temperature increases, $L_\phi$ becomes shorter than $L_{ac}$ and temperature dependent inelastic processes dominate. In this case, the logarithmic dependence gives way to the power-law dependence.

The dotted line in Fig. 3(c) represents a fit to a power-law of the form $V_{AF} \sim AT^{-p_1}$, where the parameters $A = 7.4$ and $p_1 = 1.0$ were determined from the fit. The fit is seen to be in good agreement with the data for temperatures greater than 6 K. For lower temperatures ($< 4$ K), the agreement is not satisfactory, even considering the scatter in the data. This relatively weak temperature dependence is consistent with that expected in the high-frequency limit, with $p = 2$ due to electron-phonon interactions. That we did not observe the stronger temperature dependence expected for the low-frequency regime (see Eq. 3) indicates that the frequency of the microwaves replaced $\tau_\phi$ as the dominant time scale in a mesoscopic system. The weak temperature dependence exhibited by the aperiodic PV fluctuations is consistent with previous results (4), although those authors concluded that the observed temperature dependence was weaker than expected from the theory (3). Our analysis resolves this apparent discrepancy. Unfortunately it was not possible to determine the temperature dependence for microwave fields smaller than 0.6 V/m, since for this value of the microwave field $V_{ac}$ was quite small for temperatures greater than 1.4 K.

We also studied the temperature dependence of the corresponding $h/e$ PV oscillations, $V_{h/e}$, shown as the
triangles in Fig. 3(c). From Eq. 10 we would expect a weak exponential temperature dependence since the microwaves contribute to an effective phase coherence length, \( L_{\text{eff}} \approx \left[ 1/L_{\phi}^2 + 1/L_{\text{ac}}^2 \right]^{-1/2} \), acting to weaken the temperature dependent length scale \( L_{\phi} \). In Fig. 3(c) the result of a fit to the \( h/e \) data of the form \( \exp(-\pi r/L_{\phi}) \sim \exp(-T^p) \) is shown as the solid line, where it was assumed that \( \pi r \approx L_{\phi} \) at 1.4 K and \( b = L_{\phi}^2/L_{\text{ac}}^2 \). The fit is quite reasonable over the entire range of temperature. We note that the data is not at all consistent with an exponential suppression of the form \( \exp(-\pi r/L_{\phi}) \sim \exp(-T) \) and do not show the results of such a fit here. For this reason, it seems likely that the microwave field is the dominant source of inelastic scattering as opposed to electron-electron or electron-phonon interactions. We note that this weak exponential suppression closely mimics the logarithmic \( \ln(1/T) \) and power-law \( T^{-1} \) temperature dependences observed for the aperiodic fluctuations. A deeper explanation for the observed temperature dependences awaits more extensive measurements and a full theory of the PV effect to include the case of a ring geometry.

The temperature dependences for even larger microwave fields \( (E_{\text{ac}} > 0.6 \text{ V/m}) \) were also studied. For \( E_{\text{ac}} \approx 5.0 \text{ V/m} \) the temperature dependence of \( V_{\text{AF}} \) and \( V_{h/e} \) became progressively weaker, although similar to Fig. 3(c), and we do not show the data here. For the largest microwave field \( (16 \text{ V/m}) \) used in this study (see Fig. 2), the temperature dependence was quite weak. As can be seen, \( V_{\text{AF}} \) showed very little change as the temperature was increased from 1.4 to 16 K. For this relatively high microwave field the Aharonov-Bohm oscillations are completely quenched since we are in the high-power regime. In Fig. 3(b) we show the results of a quantitative comparison of the theory, \( V_{\text{AF}} \sim q \ln(b/T) \) where the data does not quite agree with the logarithmic temperature dependence predicted by the theory. The data for \( V_{\text{AF}} \) at 1.4 K in Fig. 3(a) was shown previously in Fig. 2(a) where we saw a large increase in \( H_c \) as a function of the microwave field. It is interesting to note that despite an increase in temperature of 15 K there was very little change in the correlation field \( H_c \). It would therefore appear that the microwaves, in the moderate to high-power limit, are a much more effective source of dephasing than temperature dependent inelastic scattering mechanisms.

V. DISCUSSION

We have presented a systematic study of the PV effect in submicron-diameter Au rings as a function of microwave power and temperature. We have clearly observed the quenching of the \( h/e \) PV oscillations due to the dephasing effect of a microwave field. Such dephasing may also explain the increase in \( H_c \) for the aperiodic fluctuations, although alternative explanations for the observed behavior should be discussed. Our results for the power dependence of the PV effect are analogous to previous studies of the I-V characteristics of UCF where the magnitude of voltage fluctuations were measured as a function of the dc-voltage bias, \( V_b \). These studies showed that both the \( h/e \) and the aperiodic conductance oscillations suffered from voltage averaging and scaled as a weak power-law, \( V_b^{1/2} \), for \( V_b > V_c \), where \( V_c = E_c/e \) is the correlation voltage. This was found for dc-fields of order \( E_{dc}(= V_b/L) \sim 1 \text{ V/m} \), which is the same order of magnitude as the microwave fields used in this work. One analogous feature of the UCF results was that \( H_c \) increased as a function of the dc-voltage bias across the sample for \( V_b > V_c \) due to the introduction of a dc-voltage averaging length, \( L_E = [hD/eV]^{1/2} \) (or \( [hD/eE_{dc}]^{1/3} \)).

In the case of the PV effect it is possible for both \( L_E \) and \( L_{ac} \) to enter the problem depending on the microwave field strength and frequency. \( L_E \) was predicted by the PV theory \( \alpha \) to become significant when \( \omega \sim \omega_c \) is much larger than \( \omega_T \) and pertains to the low-frequency limit. In this case the magnitude of microwave field can be considered to be essentially constant in time and many features of the PV effect would be quite analogous to UCF. It is difficult to tell whether the observed increase in \( H_c \) in our PV studies (as shown in Fig. 3) resulted from an increase in \( L_E \) (i.e., in the dc or low-frequency limit) or \( L_{ac} = h\omega/eE_{ac} \) (strong high-frequency field) since both are inverse functions of the electric field. However, the fact that the \( h/e \) PV oscillations are clearly quenched for microwave fields larger than 5 V/m, as shown in Fig. 2(c), is a strong indication that the microwaves are dephasing. In contrast, the \( h/e \) conductance fluctuations were not quenched in response to a dc-voltage bias and grew instead according to a power-law.

For small samples at low temperatures it is also entirely possible for a finite voltage bias to heat the electron temperature above the lattice temperature. This increases the amount of inelastic scattering thus reducing \( L_{\phi} \). Heating effects due to the microwave field are difficult to rule out since they also grow with microwave field strength just as the dephasing length \( L_{ac} \) (see Eq. 3). Roughly speaking, heating effects are expected to occur as the energy gained from the voltage bias, \( eV_b \), is of order \( k_BT \). A quantitative treatment of the flow of energy from the sample to the substrate, and on to the He bath, is certainly more involved \( [13] \), although this provides a rough upper bound. For even our lowest measurement temperature (1.4 K), where \( k_BT = 120 \mu eV \), a dc electric field around 120 V/m in our 1 \( \mu \)m long wire would be necessary to cause significant heating. According to our calibrations, the microwave fields used in this study were much smaller than this, although it is possible that we have underestimated the magnitude of the microwave field or the amount of power absorbed by the sample. We note that studies of the I-V characteristics of conductance fluctuations in micron-size Au rings \( [21,22] \) ob-
served some mild heating effects for dc-voltage biases ~ 1 V/m. However, these measurements were performed at much lower temperatures (~ 50 mK) in contrast to our relatively high temperatures (~ 4 K). We concur that it is difficult to ever completely rule out the possibility of heating effects. If the electron temperature was increased due to heating from the microwaves, this would increase the electron-electron inelastic scattering rate and decrease \( L_\phi \), the precise effect we are claiming is causing the increase in \( H_c \) and the suppression of the \( h/e \) PV oscillations.

Assuming that the observed suppression of the \( h/e \) PV oscillations in Fig. 2 is not due entirely to heating, it is interesting to interpret the power dependence as resulting from multiple electron-photon scattering events. The number of such scattering events is given by the number of photons absorbed by the electron as it diffuses to the voltage contacts, as measured by the parameter \( \xi \), see Eq. 3. Given this, the results of Fig. 2(c) may be interpreted as resulting from the dephasing nature of electron-photon interactions. The PV effect may allow one to quantify, in a controlled manner, the number of electron-photon interactions. The PV effect may allow one to quantify, in a controlled manner, the number of such scattering events is given by the number of photons absorbed by the electron as it diffuses to the voltage contacts, as measured by the parameter \( \xi \), see Eq. 3. Given this, the results of Fig. 2(c) may be interpreted as resulting from the dephasing nature of electron-photon interactions. The PV effect may allow one to quantify, in a controlled manner, the number of electron-photon scattering events necessary to completely randomize the phase of the electron. However, a more precise estimate of the magnitude of the microwave field, and its coupling to the sample, would be needed to make a direct comparison. It is hoped that future theoretical and experimental efforts will be able to accurately address these fundamental and important aspects of the PV effect.

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FIG. 1. Aharonov-Bohm photovoltaic oscillations in Au ring #1 \((d = 3300 \, \text{Å} \text{ and } w = 550 \, \text{Å})\) at \(T = 4.2 \, \text{K}\). (a) The solid (dotted) line represents a field sweep with \(H\) increasing (decreasing) in magnitude. (b) The Fourier transform of \(V_{dc}\) with arrows indicating the various frequency ranges expected for the aperiodic fluctuations \((AF)\), \(h/e\), and \(h/2e\) oscillations based on the measured ring geometry. (c) Using the digital filtering procedure described in the text the aperiodic (dotted line) and the \(h/e\) oscillations (solid line) may be clearly separated.

FIG. 2. (a) \(V_{dc}\) as a function of \(H\) at \(T = 1.4 \, \text{K}\) for a moderate \((E_{ac} \approx 0.6 \, \text{V/m})\) and a high \((E_{ac} \approx 16 \, \text{V/m})\) microwave power for the \(d = 4700 \, \text{Å}\) Au ring. Two features of the power dependence are clearly visible: The correlation field \(H_c\) increases as a function of the microwave power and the \(h/e\) oscillations are greatly suppressed at high powers. (b) For the lowest microwave field \((E_{ac} \approx 0.12 \, \text{V/m})\) the \(h/e\) oscillations are almost the same size as the aperiodic fluctuations. Note the change in the voltage scale between (a) and (b). (c) \(V_{AF}\) (squares) and \(V_{h/e}\) (triangles) as a function of the microwave field \(E_{ac}\).

FIG. 3. (a) PV results for Au ring #2 \((d = 4700 \, \text{Å})\) at two different temperatures, 1.4 K (dotted line) and 4.2 K (solid line), for the moderate microwave power \((0.6 \, \text{V/m})\). (b) Close-up of data at 11 K. (c) Plot of the rms values of the data shown in (a) and (b) and for 5 other temperatures.

FIG. 4. \(V_{dc}\) as a function of \(H\) for Au ring #2 \((d = 4700 \, \text{Å} \text{ and } w = 700 \, \text{Å})\) in the high field limit \((E_{ac} = 16 \, \text{V/m})\) for two different temperatures. (a) \(V_{AF}\) at 1.4 K (solid line) and 16 K (dotted line). Note that for this relatively high microwave power the Aharonov-Bohm oscillations are completely quenched. (b) The rms values of the above data where the solid line is a fit to the logarithmic temperature dependence, \(V_{AF} \sim b \ln(a/T)\), as discussed in the text.
FIG. 1. Bartolo et al., “$h/e$ Photovoltaic Oscillations...”. Aharonov-Bohm photovoltaic oscillations in Au ring #1 ($d = 3300 \, \text{Å}$ and $w = 550 \, \text{Å}$) at $T = 4.2 \, \text{K}$. (a) The solid (dotted) line represents a field sweep with $H$ increasing (decreasing) in magnitude. (b) The Fourier transform of $V_{dc}$ with arrows indicating the various frequency ranges expected for the aperiodic fluctuations ($AF$), $h/e$, and $h/2e$ oscillations based on the measured ring geometry. (c) Using the digital filtering procedure described in the text the aperiodic (dotted line) and the $h/e$ oscillations (solid line) may be clearly separated.

FIG. 2. Bartolo et al., “$h/e$ Photovoltaic Oscillations...”. (a) $V_{dc}$ as a function of $H$ at $T = 1.4 \, \text{K}$ for a moderate ($E_{ac} \approx 0.6 \, \text{V/m}$) and a high ($E_{ac} \approx 16 \, \text{V/m}$) microwave power for the $d = 4700 \, \text{Å}$ Au ring. Two features of the power dependence are clearly visible: The correlation field $H_c$ increases as a function of the microwave power and the $h/e$ oscillations are greatly suppressed at high powers. (b) For the lowest microwave field ($E_{ac} \approx 0.12 \, \text{V/m}$) the $h/e$ oscillations are almost the same size as the aperiodic fluctuations. Note the change in the voltage scale between (a) and (b). (c) $V_{AF}$ (squares) and $V_{h/e}$ (triangles) as a function of the microwave field $E_{ac}$. 

$h/e$ Aharonov-Bohm Photovoltaic Oscillations...
R. E. Bartolo et al.
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