Observation of $h/e$ conductance oscillations in disordered metallic $T_3$ network

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We report on magnetotransport measurements performed on a large metallic two-dimensional $T_3$ network. Superimposed on the conventional Altshuler-Aronov-Spivak (AAS) oscillations of period $h/2e$, we observe clear $h/e$ oscillations in magnetic fields up to $8T$. Different interpretations of this phenomenon are proposed.

1 Introduction

Quantum interferences resulting from the phase coherence of the electronic wave functions lie at the heart of mesoscopic physics. In a mesoscopic ring pierced by a magnetic flux, such interferences lead to the well known Aharonov-Bohm (AB) conductance oscillations: the conductance oscillates with magnetic flux $\phi_0 = h/e$, where $h$ is the Planck constant and $e$ the charge of the electron.

In a line of rings, ensemble averaging leads to a strong suppression of these $h/e$ oscillations due to the random phase of the oscillations in each ring. On the other hand, interferences due to time reversed trajectories do not average to zero$^2$ and give rise to the so-called Altshuler-Aronov-Spivak (AAS) oscillations of period $h/2e$. This has been beautifully demonstrated experimentally in series of experiments on silver rings$^3$.

The same phenomenon should take place in a two dimensional array of rings. However, only the limit of very large number of rings has been explored experimentally$^4$: in this case, one clearly observes $h/2e$ oscillations around zero field, but no $h/e$ oscillations.

Renewal of interest in interference phenomena in such networks has recently arisen from the theoretical study of networks of a specific geometry called $T_3$ networks. In such a geometry, it has been suggested that interference effects should lead to a localisation of the electrons into Aharonov-Bohm cages when the magnetic flux is exactly half a flux quantum per unit cell$^5$. Such a localization leads to a strong enhancement of the $h/e$ oscillations even in large networks$^6$. This has been demonstrated experimentally on networks made from high mobility heterostructures$^7$: clear $h/e$ oscillations have been observed even at high magnetic field. However, such an experiment only tests the low disorder, small number of channels limit.

In this article, we report on magnetotransport measurements on metallic $T_3$ networks. Superimposed on the usual $h/2e$ conductance oscillations around zero magnetic field, we observe clear $h/e$ conductance oscillations. These oscillations are of strikingly similar amplitude as the $h/2e$ AAS oscillations around zero magnetic field and persist at high magnetic field of $8T$ with no significant decrease in amplitude.

2 Measurements

Samples were fabricated on silicon substrate using electron beam lithography on polymethylmethacrylate resist. The metal is deposited using an electron gun evaporator and lift-off technique. A 1 nm thin titanium layer is evaporated prior to the gold evaporation in order to improve
adhesion to the substrate. For the gold evaporation, we used a source of 99.999% purity.

The sample consists of a $T_3$ lattice containing 4500 unitary cells. Wires have a length $a = 690\,nm$, width $w = 80\,nm$ and thickness $t = 30\,nm$ (see figure 1), corresponding to a flux quantum per unit cell of $\phi_0 = 100\,G$. The resistance of the network is $24\,\Omega$ at $4.2\,K$. The elastic mean free path is evaluated to be $l_e = 28\,nm$ and the diffusion coefficient, extracted from $D = 1/3v_Fl_e$, is $D = 1.3 \cdot 10^{-2}\,m^2s^{-1}$. As expected, the wires are quasi one dimensional with respect to both the phase coherence length $l_\phi$ and the thermal length $L_T = \sqrt{hD/k_BT}$.

Resistance measurements have been carried out in a dilution refrigerator using a standard $ac$ resistance bridge technique.

Figure 1: SEM picture of the $T_3$ lattice.

Figure 2: Magnetoresistance around zero field of a metallic $T_3$ lattice at a temperature of $400\,mK$. The absolute resistance of the sample is $24\,\Omega$.

3 Results and discussion

We first concentrate on low field measurements. Figure 2 shows the relative magnetoresistance of the $T_3$ lattice around zero magnetic field at a temperature of $400\,mK$. From the envelope of the weak localization signal, we evaluate a phase coherence length of $l_\phi \approx 2\,\mu m$. Superimposed on this large magnetoresistance, we see clear oscillations of period $50\,G$ around zero field, corresponding to $\phi_0/2$ per unit cell. At higher magnetic field, small oscillations appear.
To highlight these oscillations at high field, we have subtracted from the magnetoresistance the weak localisation correction. Figure 3 displays the obtained magnetoresistance. Again, at magnetic field below 150 G, one clearly observes AAS oscillations of amplitude \( \Delta R = 6 \cdot 10^{-4} \Omega \), corresponding to \( 2.6 \cdot 10^{-2} \frac{e^2}{h} \) in terms of dimensionless conductance. As expected, these AAS oscillations decrease with magnetic field. Above \( \approx 200 \) G, period doubling occurs and other oscillations are clearly visible. These oscillations have a period of 100 G corresponding to \( \phi_0 \) per unit cell, and an amplitude of \( \Delta R = 2 \cdot 10^{-4} \Omega \), corresponding to \( 9 \cdot 10^{-3} \frac{e^2}{h} \) in terms of dimensionless conductance.

Additional magnetoresistance measurements have been performed for magnetic field up to 8 T. A typical Fourier spectrum of this measurement is displayed in figure 4. In this spectrum, one clearly observes two peaks at 0.01 G\(^{-1}\) and 0.02 G\(^{-1}\), corresponding to \( \phi_0 / 2 \) and \( \phi_0 \) per unit cell respectively. At higher frequencies, two or three additional peaks are slightly visible. It should be stressed that in this spectrum, the amplitude of the peak at \( \phi_0 \) frequency is larger than that of the peak at \( \phi_0 / 2 \) frequency.

Two effects can be invoked in order to explain the observation of these unexpected \( h/e \) oscillations. First, they can be attributed to reminiscence of the Aharonov-Bohm conductance oscillations in this (otherwise peculiar) network of rings. If such oscillations have been observed for a line of rings, they have never been observed in a network of rings, due to the lack of sensitivity and the very large number of ring. In this case, the relevant parameter is the ratio between the amplitude of the \( h/e \) (AB) and the \( h/2e \) (AAS) component. However, \( h/e \) oscillations should vanish like \( 1/\sqrt{N} \) with \( N \) the number of rings: in our case, both components have roughly the same amplitude. Only a detailed calculation of this effect for this particular geometry should allow meaningful comparison between experiment and theory.

The persistence of \( h/e \) oscillations in this \( T_3 \) lattice could also be attributed to the localisation of the electrons. It has been shown theoretically and proven experimentally that in such a geometry, Aharonov-Bohm cages lead to a striking robustness of the \( h/e \) component of the conductance oscillations against disorder averaging, at least in the single channel limit. In this context, it is tempting to consider our observation as a signature of the Aharonov-Bohm cage effect in the multi channel limit. The rich content in harmonics observed in the Fourier spectrum (see figure 4) could be another evidence of this Aharonov-Bohm cage effect. Again, a detailed calculation of these subtle localisation phenomena in the multi-channel limit is needed to give a definitive conclusion on our observation. In addition, measurements on square lattices are necessary for a complete understanding the observed \( h/e \) oscillations.
Figure 4: Fourier spectrum of the magnetoresistance of a metallic $T_3$ lattice. The magnetic field range is $0.2 - 8T$.

4 Conclusion

We have measured the magnetoconductance of a metallic (gold) $T_3$ lattice made of 4500 unitary cells. Superimposed on the usual Aronov-Altshuler-Spivak oscillations with period $h/2e$, we observe clear oscillations with period $h/e$ which persist at high magnetic field up to $8T$. The Fourier spectrum of the magnetoconductance reveals a rich content in harmonics.

This first observation of $h/e$ conductance oscillations in a network can be attributed either to the reminiscence of the Aharonov-Bohm oscillations in each cell, or to the geometrical localisation effect related to the presence of Aharonov-Bohm cages. In both cases, a detailed theoretical calculation is needed to give a definitive statement. Additional measurements on networks of different sizes and topologies ($T_3$ lattices vs square lattices) are necessary to get a deeper comprehension of these subtle interference effects.

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