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13. ABSTRACT (Maximum 200 words)

This Technical Report summarizes the results of a three-year research effort in the field of mesoscopic physics conducted by John M. Hergenrother at Harvard University., supported by a JSEP Fellowship. During the first two years, Hergenrother was a graduate student; during the final year, he was a postdoctoral research associate. The results have been reported in 11 publications which are listed in the Report. The primary focus of the work was charge transport in single-electron tunneling transistors, with both normal and superconducting leads. This work illuminated the role of Andreev tunneling processes in transferring pairs of electrons from normal to superconducting electrodes, the importance of the Coulomb blockade for Cooper pairs of electrons, and the possibility of developing an ultrasensitive microwave detector capable of detecting individual photons of frequency above 80 GHz.

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Final Technical Report

John M. Hergenrother, Joint Services Electronics Program Graduate and Postdoctoral Fellow

This report summarizes the result of a three-year research effort in the field of mesoscopic physics conducted by Dr. John M. Hergenrother at Harvard University. During the first two years of this period, Dr. Hergenrother was a graduate student working with a more junior graduate student, Ms. Jia G. Lu, under the direction of Prof. M. Tinkham. In the final year of the three-year grant, Dr. Hergenrother worked in the same group as a postdoctoral research associate in collaboration with a graduate student named Ms. Sarah L. Pohlen. Most of the results discussed in this report have been previously published in various journals [1-7] and described in detail in Dr. Hergenrother's doctoral thesis [8].

1. Charge Transport in the Normal-Superconductor-Normal Single-Electron Transistor

In the single-electron transistor, a small metal island (typically 70 nm wide by 20 nm thick by 2 μm long) is coupled to two bias leads through ultrasmall, high-resistance tunnel junctions with capacitances C_1 and C_2. These junctions are typically 70 nm by 70 nm in area. The island is also coupled capacitively to a gate electrode through a capacitance C_g. The total capacitance of the small metal island to the external circuit, $C_\Sigma = C_1 + C_2 + C_g$, is so small (typically < 1 fF) that at temperatures below 1 K, the characteristic energy required to add a single electron to or subtract a single electron from the island ($E_C = e^2/2C_\Sigma$) is the dominant energy in the problem. In this regime, the behavior of the device is dominated by so-called single-electron charging effects. In a typical transport measurement, the devices are cooled to $T < 50$ mK and the current through the device (i.e. from one bias lead through the island to the other bias lead) is measured as a function of the gate voltage V_g. For low bias voltages and suitable gate voltages, it is energetically unfavorable to change the number of electrons on the islands even by one. This phenomenon is know as the Coulomb blockade.

In his first year of JSEP support, Hergenrother studied a particular version of this device known as the normal-superconductor-normal (NSN) single-electron transistor. In this version, the island is made of superconducting Al, the tunnel junctions are aluminum oxide, and the bias leads are normal-metal Au. Hergenrother conducted as extensive study of charge transport through this device. He showed that at low bias voltages (V significantly less than $2\Delta/e$, where Δ in the energy gap in the superconducting island), single-electron tunneling is suppressed and that current is transported through a two-step cycle of Andreev reflection events [1, 2, 8]. In the first step of this cycle, two normal electrons tunnel from the negatively-biased lead to form a Cooper pair on the island. In the second step, a Cooper pair tunnels off the island through the opposite junction to form two electrons in the positively-biased lead. Apart from a net of two electrons which have travelled through the system, the original state is restored. This Andreev cycle gives rise to currents of order 1 pA. When applied to this device, the simplest theory of Andreev reflection (in which any phase coherence between electrons in the normal metal leads is ignored) predicts currents of order 1 fA. Thus, Hergenrother's experimental results indicated that one must consider phase-coherent Andreev reflection in order to understand the large magnitude of the Andreev cycle current.

Hergenrother collected an extensive set of transport data for the NSN single-electron transistor. Through a careful analysis of the various bias voltage thresholds for Andreev reflection in the NSN single-electron transistor, he showed that in analogy to single-electron tunneling, Andreev reflection (two-electron tunneling) is also subject to the Coulomb blockade. Hergenrother's data show that the Andreev cycle current is peaked near $Q_o = (2n+1)e$, where n is an integer and the gate charge $Q_o = C_g V_g$. The $2e$ periodicity of the current that he observed at low bias voltages indicates that even-odd electron number (parity) effects [9 -11] dominate the behavior of the NSN single-electron transistor in this regime.

Dr. Hergenrother also identified an interesting phenomenon know as quasiparticle trapping. As the bias voltage is increased to approximately Δ/e, it becomes energetically favorable for a single quasiparticle to enter the island. Since it takes a relatively long time of order 1 μs for this single quasiparticle to tunnel off the island, it is effectively trapped on the island. While this quasiparticle is trapped, the Andreev cycle is blocked for energetic reasons. The net effect of this quasiparticle trapping is that it leads to a significant *decrease* in the time-averaged current through the device with *increasing* bias voltage.

2. Effects of Photon-Assisted Tunneling in the Single-Electron Transistor and Photon-Activated Switch Behavior

All of the results discussed so far were for samples that were extremely well shielded from cryogenic blackbody radiation emitted by surfaces at temperatures significantly above 50 mK. In a complementary body of work, Dr. Hergenrother experimentally demonstrated that exposing a single-electron transistor to small amounts of cryogenic blackbody (microwave) radiation can lead to photon-assisted tunneling. Photon-assisted tunneling greatly increases the rates of energetically unfavorable single-electron tunneling events and dramatically affects charge transport in the NSN and the all-superconducting (SSS) single-electron transistor systems. Even when there are no measurable electron heating effects at 50 mK, small amounts of microwave radiation produce a variety of new features in the experimental dc transport data [2, 4-6, 8]. Dr. Hergenrother performed extensive computer simulations of the effects of photon-assisted tunneling. He showed that the dc experimental data are in excellent quantitative agreement with these simulations.

The most interesting feature that arises in the presence of small amounts of microwave radiation is a striking "secondary" peak at $Q_o = 0$ in the dc current through the device. This current peak is labelled "secondary" in order to distinguish it from the "primary" peaks near $Q_o = (2n+1)e$ discussed in the previous section. Dr. Hergenrother pointed out that this secondary peak arises as follows. Suppose that $Q_o = 0$ and that the island initially contains an even number of electrons. In this case, at low bias voltages and at temperatures less than about 300 mK, all electrons in the island are bound in Cooper pairs. In the absence of photon-assisted tunneling, both single-electron tunneling and Andreev reflection are energetically unfavorable and do not occur at $Q_o = 0$. However, if a single photon of sufficient energy (corresponding to $f > 80$ GHz) is absorbed, a single electron from one of the bias leads can tunnel onto the island to form a quasiparticle there. As described is the previous section, this quasiparticle is trapped on the island for a time of order 1 μs. The presence of this single quasiparticle makes it energetically favorable for electrons to tunnel through the system *two at a time*. In the NSN single-electron transistor, this current is due to the Andreev cycle (~ 1 pA), but in the SSS system it takes the form of a much larger (up to 1 nA) finite voltage "supercurrent" of Cooper pairs. In short, the absorption of a single microwave switches the device from a low- to a high-current state and the device automatically resets itself after about 1 μs. The single-electron transistor with a superconducting island is referred to as a photon-activated switch [4-6] because *many* electrons can pass through the device after it has been switched on by a *single* photon. Dr. Hergenrother experimentally demonstrated that more than 100 electrons can tunnel through the system for every absorbed photon. His calculations suggest that in an optimal SSS sample, each absorbed photon gives rise to a pulse of as many as 10^4 electrons, making these devices extremely sensitive to microwave radiation.

3. Working Towards a Detector of Individual Microwave Photons

Dr. Hergenrother and his current collaborator, Ms. Sarah L. Pohlen, hope to use the extreme sensitivity of the single-electron transistor to microwave radiation to build a detector with the maximum possible sensitivity, i.e. one that is capable of resolving individual microwave photons. In order to see how they plan to achieve this, consider the following. The dc transport data show that Dr. Hergenrother and Ms. Pohlen have the sensitivity to readily detect the current that is induced even by such a low rate of photon absorption that the current is less than one percent of the full primary peak current, i.e. when the switch is closed only 1% of the time. Since the quasiparticle trapping time is about 1 μs, this implies one photon absorbed per 100 μs.

Accordingly, if this current could be examined with time resolution of 1 μs and sufficient current resolution, it should appear as a random sequence of 1 μs pulses at an average interval of 100 μs. This would allow the time-resolved observation of individual microwave photons, something never before achieved. To actually accomplish this time resolution, however, one requires a cryogenic device capable of power gain and of lowering the impedance of the device for better impedance match with the coaxial cable used to bring a broadband signal out to room temperature amplifiers, with a sufficient signal/noise ratio.

Dr. Hergenrother and Ms. Pohlen have attacked this challenging problem by identifying commercially available GaAs MESFETs which can be used at 1 K. They have designed and built broadband, very low noise cryogenic amplifiers with 1 MHz bandwidth using them. In order that the full bandwidth of the amplifier be realized, the amplifier input must be physically very near the single-electron transistor (which is attached to the mixing chamber of a ^{3}He/^{4}He dilution refrigerator) to minimize lead capacitance. On the other hand, the heat load from the cryogenic amplifier must be deposited to the 1 K pot of the dilution refrigerator, since it greatly exceeds the capacity of the mixing chamber. These conflicting requirements have required unusual care in designing the physical layout of the electrical and thermal connections. Recently, these requirements have been reconciled to a satisfactory degree, and experimental preparations are moving forward.

If successful, this will be the first device ever built which is capable of counting individual microwave photons (80 GHz and above), as opposed to the optical photons counted by conventional photomultipliers. Thus, it will allow one to probe photon statistics in a new, much lower energy regime, in which the classical wave approximation is usually satisfactory. It should be noted that as an important added benefit, the coupling of single-electron transistors to these high-performance cryogenic amplifiers will open the door to a wide range of other experiments probing the time-resolved dynamics of electronics processes at low temperatures. For example, a single-electron transistor operating as a charge-sensitive electrometer coupled to such an amplifier should be able to resolve fractional electronic charge changes in a microsecond time scale.

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