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Single Charge Electronics-Time Correlated Tunneling in Ultrasmall Tunnel Junctions

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A new branch of electronics, that has been named "single electronics", is based upon correlated tunnel events in ultrasmall junctions. The tunneling of single electrons can be controlled by sub-electron changes of the charge distribution. Time correlated tunneling is stressed in this review and analogies are drawn with well known Josephson effects. Bloch type oscillations, where charges tunnel one by one, can occur with frequency determined by the current, I=qf, where q=e for single electrons and q=2e for electron pairs. This frequency to current relation may lead to a current standard very much related to the voltage standard based upon Josephson tunneling in a microwave field.

1 Introduction

The number of electrons tunneling per unit time is very large in a "usual" tunnel junction and we need not care about single tunneling events that occur statistically. The change in junction voltage $\Delta V=e/C$ (where C is the junction capacitance) for a single electron tunnel event is small, typically 0.1 μV for a 10 μm x 10 μm large junction, and it is masked by thermal fluctuations . However, if we diminish the linear dimensions of the junction by a factor of 100, the voltage fluctuations increase to the level of 1 mV (i.e. corresponding to 10 K) and become observable at helium temperature.

The capacitive charging energy, $E_C=e^2/2C$ due to an extra electron, may become the dominant energy in ultrasmall tunnel junctions. The conditions are that it should be larger than thermal fluctuations, k_BT, and quantum fluctuations, h/τ, where the lifetime τ is typically the RC charging time. In other words, $C<e^2/2k_BT$ and the resistance $R>R_Q=h/4e^2\approx 6.5$ kΩ. (R is the smaller of the junction resistance, R_T, and the load resistance due to the environment, R_S.) Tunneling may be possible only for $|Q|>e/2$, i.e. $|V|>V_{threshold}=e/2C$ (2e and e/C, respectively, for pairs). No current will pass the tunnel junction if the voltage is less than $V_{threshold}$, resulting in a Coulomb blockade of tunneling. We can compare with the zero voltage Josephson state in superconductive tunneling where there is no voltage drop below a critical current bias.

With a constant bias current forced through the junction, the additional charge on the junction capacitance will build up to e/2, an electron will tunnel, changing the junction charge to -e/2, the charge builds up, etc. Relaxation oscillations of both charge and voltage occur which are called single electron tunneling (SET) oscillations. The oscillation frequency is determined by the current $\langle I\rangle=ef$. The oscillation will be broadened by a shunt admittance, by increasing temperature, or by a larger bias current. Again, we can compare with a Josephson junction where a voltage across the junction will lead to current oscillations with $f=V/\Phi_0$.

The Coulomb blockade can be completely wiped out by a low impedance electro-magnetic environment. If no precautions are taken, the stray capacitances, C_s, from the leads and other sources will completely dominate over the junction capacitance as the effective capacitance will be the sum of the two. It is not the dc resistance but the frequency dependent impedance that the junctions sees which matters. The microstrip leads to the tunnel barrier can be considered as transmission lines and they will be of low impedance (ca 100Ω) at high frequency ($f\approx I/e$) if precautions are not taken. Very small resistors with resistance larger than RQ can be connected in series very close to the junction in order to minimize the effect of the stray capacitance of the leads. An alternative scheme to isolate the junction from the environment is to embed the junction in an array of high resistance junctions .

In a superconducting tunnel junction, one has to take into account not only the charging energy but also the Josephson coupling. When the charging and the Josephson energies become of the same order, there may occur oscillations of the same kind as in a solid when the kinetic energy is of the same order as the periodic potential from the lattice. Bloch type oscillations in superconducting junctions were predicted even before SET oscillations but they have been more difficult to verify experimentally as the parameter range for their detection is rather limited. They are supposed to occur with frequency $f=I/2e$. The dc I-V curve will be characterized by a Coulomb blockade of pair tunneling and a back-bending towards the zero-voltage branch.

2 Sample Fabrication

In order to study single charge tunneling, we must fabricate junctions that are small, less than 100 nm square, to obtain a sufficiently small capacitance. The junction resistance must be much be higher than the quantum value, and a configuration must be chosen such that stray capacitances (between the electrodes and to the ground plane) are minimal. To further reduce the influence of the environment, resistors may be placed close to the junctions. Charges moving between traps in the substrate may strongly interfere with the Coulomb blockade effects and the materials should be chosen to minimize such noise contributions.

Electron beam lithography techniques allow the fabrication of sufficiently small tunnel junctions to study single charge tunneling phenomena. A useful fabrication technique was developed by Niemeier and by Dolan. It uses a hanging mask and is self-aligned as the same mask is used for evaporation from different angles. The overlap between top and bottom electrodes is determined by the angles. A tunneling barrier is formed by oxidizing the bottom electrode before the top one is deposited. Using aluminium, this results in junction resistances of the order of 1-1000 kΩ per junction for an overlap area of about 70 nm x 70 nm. The junction capacitance is typically a few times 10^{-16} F while the stray capacitance C_0 between the electrodes of neighboring junctions can be 10^{-17} to 10^{-16} F.

Protecting resistors have to be placed close to the junctions to avoid stray capacitance. They are generally difficult to fabricate. In the experiments to be discussed here, 10-30 µm long, 0.1 µm wide and 5-7 nm thick strips of Cr, NiCr, AuPd, or Ge/Pd layers were used. The sheet resistance was 300-2000 Ω/square.

3 Time Correlated Tunneling. SET and Bloch Oscillations

The expected oscillator power is small in a junction with a low tunnel current. Furthermore, the high resistance junction is severely mismatched to any receiver that typically has an input impedance of the order of the one of free space, i.e. a few hundred ohms. Hence most of the power will be reflected and the chance to detect it directly with conventional receivers will be small. The situation is similar to the one that faced the first, large area and low resistance Josephson oscillators. In that case, a solution was found to the problem, namely to observe RF induced current steps in the I-V curve. Similarly one expects steps in the I-V curve of an ultrasmall tunnel junction, but now in voltage and at currents $I=nef_{ext}$ (or $n \cdot 2ef_{ext}$ for the Bloch case). Such steps were first observed in 1D arrays of Al junctions for $n=\pm1$ and ±2.

The first evidence for Bloch oscillations in well controlled junctions was seen in experiments using Al or Pb alloy junctions that were well protected from the environment by large resistors. When E_J was of the same order as E_C, it was possible to detect phase locking of Bloch type oscillations to external microwaves in the range of f_{ext}=0.4-10 GHz in junctions with normal state resistances of 3-60 kΩ. The location in current of the resistance peaks fitted the relation $I=2ef_{ext}$, there was no such frequency dependent location in voltage. Later experiments using two orders of magnitude lower RF power which was modulated at low frequency, also induced structures in the response curves which followed the Bloch relation $I=2ef_{ext}$.

Bloch oscillations were also observed in double-junction structures with resistors. The effective capacitance of such a structure is smaller than the capacitance of a single junction ($C_{eff} = C/2$ in the case of a small capacitance of the central, control electrode). This increases E_C. Keeping the same E_C, we can use larger areas of the junctions in an array and, thus, increase E_J.

The Josephson coupling can be tuned and completely suppressed by a magnetic field. Hence it is possible to go from Bloch type oscillations, with $I=2ef_{ext}$, to SET oscillations with $I=ef_{ext}$. At low fields there is a pronounced Coulomb blockade of Cooper pairs at low bias followed by a Josephson current contribution. As the field is increased, the Josephson contribution is diminished and the Coulomb blockade region is widened to the single electron value. Applying RF power at no or low magnetic field, a peak structure is appearing at a location of $I=2ef_{ext}$ as the power is increased. This is supposedly due to pair, or Bloch type, oscillations. As the Josephson currents are quenched by a magnetic field, SET oscillations start to dominate. A complication is that the peak falls at intermediate current locations in the transition region as if the oscillator is jumping (like a relaxation oscillation) between two states with the relative time spent in each state determining the average current.

4 Current Standard

Induced current steps in Josephson junctions can be utilized in a voltage standard where voltage is related to frequency. The latter can be determined with very high accuracy. With an N junction array a well defined voltage can be obtained (at $V=N \cdot n\Phi_0 f_{ext}$) at a level as high as 10 V, which can be used to calibrate secondary standards. An accuracy of the order of 10^{-8} is realized in practice today.

It may be possible to realize current standards based upon the RF induced voltage steps in the I-V curves of single charge tunneling devices, either interacting with SET or Bloch oscillations. Sharper step structures than in free running oscillator modes can be obtained in so called turnstiles or in charge pumps. These are based upon the controlled transfer of one electron each time a charge is induced on one (or several) intermediate electrode(s) of an array by a gate electrode. The accuracy of the early current standard prototypes, that have been developed hitherto, is limited to about 10^{-3}. It has to be bettered about three orders of magnitude in order to compete with presently used current balances. One cause of the limited precision is the simultaneous quantum tunneling of charge through several junctions during a period. This may be reduced by including more junctions in the turnstile arrays. Another problem is the low current level; a frequency of 60 MHz corresponds to about 10^{-11} A. One solution, that may be difficult to realize, is to use a large number of arrays coupled in parallel and, finally, a superconducting current comparator. The connection in parallel would correspond to the many junctions coupled in series in the voltage standard case.

Most of single charge tunneling effects have their counterparts in the better known, and already explored, Josephson effects . Similar phenomena can be described, and predicted, in the same formalism if a number of variables are treated as corresponding entities. High performance applications, that have common roots, may result for both cases.

Furthermore, it is possible to transform from the well developed Josephson regime to the fully developed Coulomb blockade region by changing two sets of parameters: the Josephson energy relative to the charging energy and the tunneling resistance relative to the quantum resistance. Interesting phenomena like Coulomb blockade of Cooper pairs and Bloch oscillations occur in the region between the Josephson and single electron tunneling regimes. It should be specially pointed out that it may be possible to tune the Josephson coupling strength with the aid of a magnetic field and hence scan an interesting parameter region in one and the same tunnel junction. Examples of this, like the transformation from Bloch to SET oscillation induced peaks in the I-V curve under RF irradiation, have been discussed.

Thrilling applications of supersensitive, sub-electron controlled single electronics may become a reality in the future if still smaller structures can be fabricated in a controlled way, giving a possibility to operate devices at a manageable temperature. A novel current standard, based on a well defined frequency, has a fair chance to be realized if coherence and coupling problems can be solved.