Charge Imbalance Effect Studied in Low Temperature V-I Characteristics of Lateral Superconductor/Insulator/Normal Junctions

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Electrons injected from a normal metal to a superconductor remain unpaired (quasi particles) for a short time. Within the time, there exists a quasi particle disequilibrium. The charge imbalance effect of quasi particles is the inhomogeneous charge distribution in a momentum space of superconductors. Here, we uncovered voltage-current (V-I) characteristics of small S/I/N tunnel junction devices which clearly exhibit the charge imbalance effect, by conducting the measurement in low temperatures.

The device consists of a narrow wire (width 0.13μm) of superconducting Al and several small Al/AlOx/Au tunnel junctions. (Figure 1) The device was fabricated using an electron beam lithography and a shadow evaporation technique. Measurements were performed using dilution refrigerator with signal leads carefully filtered with RCL and copper powder filters.

Electrons were injected at an injector junction. The V-I characteristics were measured at a detector junction. Figure 2 is the low temperature (T=70mK) V-I characteristics for the set of an injector and a detector placed 2μm apart. The measured V-I curves are strongly dependent on injection current I_{inj}. The V-I characteristics do not crosse the origin except for the data with small I_{inj}. This is because there exists excess currents stemming from charge imbalance effect.

The excess current is independent of detector bias voltage V. This can be seen by comparing the curves with the same $|I_{inj}|$ value but different signs. The fact that the two curves are parallel means that the difference of current at the same bias voltage is independent of detector bias voltage.

The excess current is not a simple linear function of I_{inj}. This excludes the possibility that the measured current is leakage. We also observe in the I_{inj} dependence of zero bias conductances that effective system temperature deviates depending on I_{inj}.

The voltage V_c at which the detector junction current vanishes gives the electro chemical potential difference between electron and hole branches. Typically it is of order of nano volt in high temperature measurements. The observed V_c is about 130μV at I_{inj}=60nA, which is much larger than the past experiments in high temperatures. It is comparable to superconducting energy gap Δ/e=220μV. Considering current step structure in V-I characteristics, non-vanishing charge imbalance results in the V_c close to Δ/e in sufficiently low temperatures.

We also measured the spatial relaxation of charge imbalance effect by measuring the excess current with different injector-detector distance. The excess current diminished exponentially. The relaxation length was estimated to be about 4μm.

So far charge imbalance effect has been mainly studied in conjunction with the branch imbalance relaxation time and phase slip behavior, near $T=T_C$ where energy gap for superconductivity is small. In those temperature regime, the large bias voltage dependent current from thermally excited quasi particles makes difficult observing the charge imbalance effect in the V-I characteristics. They used the current balance method to detect charge imbalance using SQUID because of the small voltage signal. On the other hand, we performed the measurements in a much lower temperature regime and observed the manifest charge imbalance effect in V-I characteristics. Our lateral device structure has advantages in fabricating complicated structures over the vertical ones used in the past experiments. Moreover lateral small structures ensure the one-dimensional quasi-particle diffusion as well as the local measurement of electronic state of superconducting narrow wires.

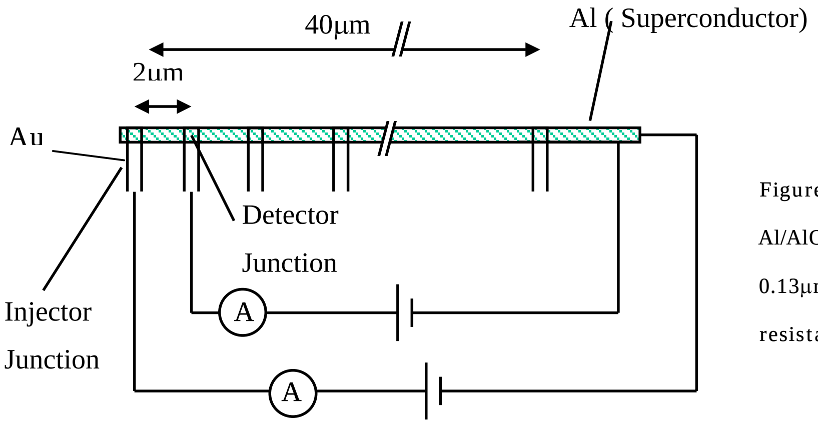

Figure 1 Schematic diagram for device structure of Al/AlOx/Au tunnel junctions. Width of Al wire is 0.13μm. The junction area was 0.017μm². The junction resistance was adjusted to be between 5kΩ-10kΩ.

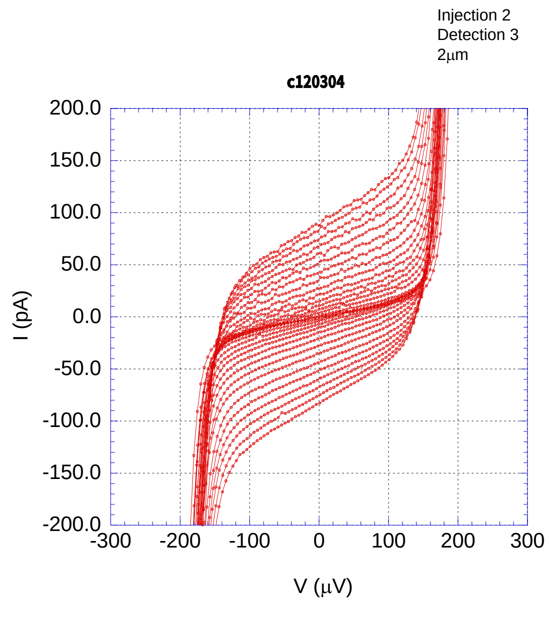

Figure 2. V-I characteristics of detector junction. *T*=70mK. From bottom to top injection current was varied from -60nA to 60nA with 4nA step. Note that the current data were the *measured* data without offset for display.