Phase Periodic Thermopower in Normal Metal/Superconductor Nanostructures

A. Parsons [a], I. Sosnin [a,1], V.T. Petrashov [a]

[a] *Royal Holloway University of London, Egham, Surrey, TW20 0EX, U.K.*

Abstract

The phase-periodic thermopower in diffusive Sb/Al nanostructures (Andreev interferometers) has been measured in the temperature range $0.3 < T < 1.5K$. Thermoelectric voltage arising between two normal probes was compared to that between normal and superconducting probe. In both cases, the maximum amplitude of oscillations was of the same order of magnitude and was reached at heating currents corresponding to the temperature of superconducting transition, where $\mathrm{d}R/\mathrm{d}T$ also has its maximum, R is the resistance of Sb wire. Remarkably, at low heating currents the two show drastically different behavior, indicating that there are probably two different mechanisms for thermopower in these structures.

Key words: mesoscopic superconductivity; thermoelectric phenomena

In normal diffusive metals the thermopower, Q, usually follows Mott's relation [1] containing a derivative of conductivity σ with respect to energy ε taken at the Fermi level

$$Q = \frac{\pi^2}{3}\frac{k_B^2 T}{e}\frac{1}{\sigma}\left\{\frac{\partial\sigma}{\partial\varepsilon}\right\}_{\varepsilon=\varepsilon_F}, \qquad (1)$$

where k_B is the Boltzmann constant and e is the electron charge.

The thermoelectric properties of a normal metal (N) in contact with a superconductor (S) are strongly modified by the proximity effect. Some recent experiments on mesoscopic N/S structures have reported thermopower orders of magnitude larger than that in normal metals [2], which is in line with theoretical evaluation [3]. Theory also predicts that Mott's law breaks down for left-right asymmetric N/S structures with energy dependent transmission/reflection probabilities [3]. Recently, a novel mechanism for thermoelectric voltage has been proposed theoretically, namely, the voltage between N and S circuits may appear due to nonequilibrium branch imbalance in the N film created by a temperature gradient [4]. The thermopower associated with this effect is also predicted to be giant compared not only with that in normal metals but also with that measured by all normal probes on the same structure.

The purpose of the experiment reported here is to check the validity of Mott's relation and to compare thermoelectric voltage arising between two N-probes, V_{N-N}, with that between N- and S-probes, V_{N-S}. Semimetal Sb was chosen as a normal part because of its large classical thermopower which can be measured in the same experiment.

The structures had geometry of Andreev interferometers with superconducting loop, 60nm thick Al, connected to normal metal part, 40nm thick Sb, (fig. 1). The upper part of the structure was used to measure thermopower of Andreev interferometer, while the lower part, to measure classical thermopower. The heating current was applied to the central electrode so that a temperature gradient was created in the normal part of the Andreev interferometer and in the control all-normal part. The heating current was a mixture of dc signal and low frequency ac signal of $0.5\mu A$ amplitude. The thermoelectric voltage was detected on the

[1] E-mail: i.sosnin@rhul.ac.uk

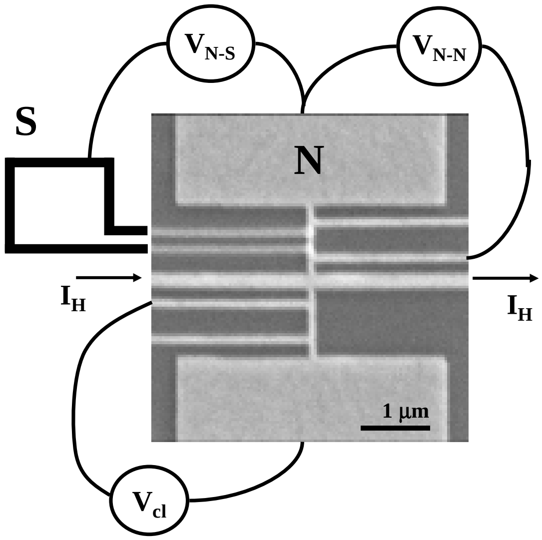

Fig. 1. SEM micrograph of measured sample. Normal part is 40nm thick Sb; superconducting loop is 60nm thick Al.

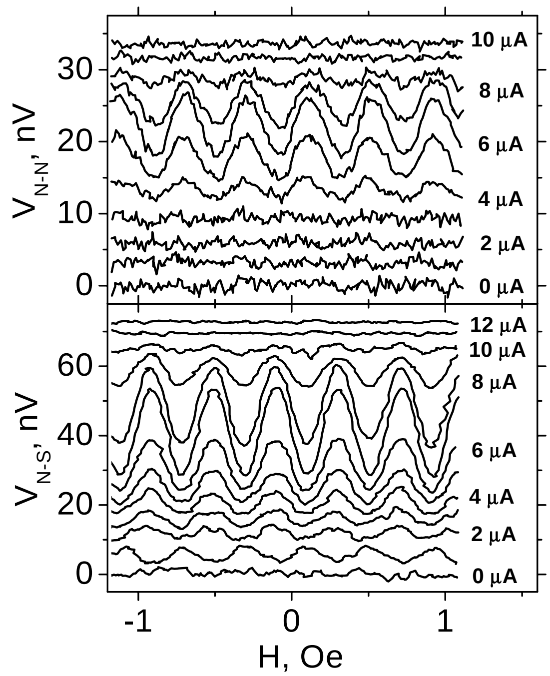

Fig. 2. Oscillations of thermoelectric voltages V_{N-N} and V_{N-S} versus magnetic field at different levels of dc heating current. Curves are offset for clarity.

frequency of ac signal by a lock-in amplifier (see fig. 1).

Figure 2 shows oscillations in V_{N-N} and V_{N-S} *vs* applied magnetic field at various values of dc heating current. In both cases, maximum amplitude of oscillations is reached at heating currents from $6\mu A$ to $7\mu A$. Measuring the dependence of resistance oscillations in the interferometer on the same dc heating current and on temperature, we have established that $7\mu A$ corresponds to the temperature of superconducting transition in the Al loop. Thus, the maximum thermopower coincides with the maximum in dR/dT, which may play role of $\left\{\frac{\partial\sigma}{\partial\varepsilon}\right\}_{\varepsilon=\varepsilon_F}$ in (1). This suggests that close to the superconducting transition, the thermopower in our structures probably follows Mott's relation.

While V_{N-N} and V_{N-S} show approximately the same behavior at high heating currents, the two are drastically different at low heating currents. There are no oscillations in V_{N-N} at currents lower than $4\mu A$. In contrast, V_{N-S} shows relatively large oscillations at currents as low as $1\mu A$. Moreover, the reversal of oscillation occurs between $1\mu A$ and $2\mu A$. This reversal of oscillations has also been observed on several other structures of slightly different geometry and will be reported in detail elsewhere. This remarkable difference between oscillations in V_{N-N} and V_{N-S} at low currents favors the explanation that the effect considered in ref. [4] is probably at work here.

Finally, the geometry of our sample allowed us to measure classical thermopower on all-normal part. No V_{cl} has been detected within the experimental noise. This result shows that both V_{N-N} and V_{N-S} are indeed giant compared to V_{cl}, in agreement with theory [3,4].

In conclusion, we have measured oscillations of thermopower in mesoscopic Sb/Al Andreev interferometer using $N-N$ and $N-S$ probes. In both cases maximum thermopower is reached when dR/dT also has its maximum, thus establishing the connection of thermopower in our N/S structures with Mott's relation (1). Remarkably, at low heating currents the two show completely different behaviors, suggesting that there may be two different mechanisms for thermopower. We also find that thermopower in our N/S structures is at least 50 times larger than classical diffusion thermopower in the same geometry without superconductors.

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