Application of Superconductor-Semiconductor Schottky Barrier for Electron Cooling

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Abstract

Electronic cooling in superconductor - semiconductor - superconductor structures at sub kelvin temperatures has been demonstrated. Effect of the carrier concentration in the semiconductor on performance of the micro-cooler has been investigated.

Key words: Electronic cooling; superconductor-semiconductor junction; Schottky barrier

1. Introduction

During the past decade attention has been paid to a new type of solid-state microcoolers based on electron tunneling in NIS (normal metal - insulator - superconductor) structures [1–6]. These coolers are promising for low temperature sensor applications and in particular for hot electron bolometers [6]. NIS refrigerators may be used for both cooling the whole sensor or for direct cooling of electrons in the detector. Significant progress in the development of NIS and SINIS refrigerators has been achieved since the first demonstration of electron cooling in the NIS structure [1]: considerable cooling of electrons in normal metal [2,3], and of thin insulating membrane [4] has been demonstrated.

Recently a semiconductor - superconductor (Sm-S) structure with Schottky barrier has been suggested for electron refrigeration [7]. In this structure there is no insulator layer and the Schottky barrier is formed at the interface between the semiconductor and the superconductor. Moreover, variation of the doping level in the semiconductor significantly affects the resistance of the Schottky barrier [8] and the electron-phonon coupling in the semiconductor and it can be used for modification of the cooler device parameters in a very wide range.

The operation of the refrigerator based on S-Sm-S structure is similar to that of SINIS [7]. Cooling is based on the existence of the energy gap in the superconductor which affects tunneling of the quasiparticles between the superconductor and the normal electrode. The maximum cooling power for an S-Sm-S cooler with two symmetric junctions at $T << T_c$ (T_c is a critical temperature of the superconductor) is given by [2,4]

$$P_{max} \approx 2 \times 0.6 \frac{\Delta^{1/2}}{e^2 R_T} (k_B T_e)^{3/2}, \qquad (1)$$

where R_T is the normal-state tunneling resistance for a single junction, Δ is the energy gap of the superconductor and T_e is the electron temperature in the semiconductor. The maximum cooling power is obtained when the voltage drop across each junction is slightly below Δ/e. The operation of the cooler device depends on the thermal coupling of the cooled electron system to its environment. The heat flow from phonons (temperature T_{ph}) to electrons (T_e) is given as [9]:

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$$P_{el-ph} = \Sigma V(T_{ph}^5 - T_e^5), \quad (2)$$

where V is the volume of the normal electrode, and Σ is a material-dependent constant, which in SOI films under investigation is of the order of $10^8 W/K^5 m^3$. The electron temperature corresponding to the maximum cooling can be found by solving equation for the power balance in the system:

$$P_{max} + P_{el-ph} = 0 \quad (3)$$

Additional heating mechanisms such as a heat leak through the junction due to back tunneling of the hot quasiparticles and recombination phonons should be taken into account in particular for the devices with low resistance of the junctions [6].

2. Samples

Heavily doped n-type silicon with different carrier concentration (from $4 \times 10^{19} cm^{-3}$ to $1.6 \times 10^{20} cm^{-3}$) was used as a semiconductor in our S-Sm-S cooler devices. The characteristics of the samples are given in Table 1. All our samples were silicon-on-insulator structures with 400 nm thick buried oxide layer. The 300 nm thick $Al - 1\%Si$ film was used as a superconductor electrode. The area of the rectangular S-Sm-S cooler sample used in our experiments was $20 \times 30 \mu m^2$, the size of the cooling contacts and the thermometer contacts was $5 \times 18 \mu m^2$ and $3 \times 3 \mu m^2$, respectively (Fig. 1a).

A $^3He/^4He$ dilution refrigerator was used for measurements in the temperature range between 50 mK and 1 K. The electron thermometry in the semiconductor is based on a high temperature sensitivity of the quasiparticle tunneling: current-voltage characteristics of a S-Sm-S structure strongly depend on the electron temperature in the semiconductor at $T < T_c$ (Fig. 1b). We used a pair of current biased $3 \times 3 \mu m^2$ junctions to probe the electron temperature in the normal electrode.

Table 1
Characteristics of the samples. N - carrier concentration, d - thickness of the silicon film, R_{sq} - sheet resistance of the silicon film at 1.5K, R_T - normal-state tunnel resistance of $5 \times 18 \mu m^2$ junction, P_{max} - maximum cooling power at 175mK.

WAFER	S1A	S1F	S1G	S1H
N [$\times 10^{19}$ cm^{-3}]	4.0	6.7	12	16
d [nm]	70	58	58	58
R_{sq} (1.5 K) [Ω]	148	109	88	77
R_T (1.5 K) [Ω]	∼750	∼130	∼40	∼20
P_{max} (175 mK) [pW]	∼1.3	∼7.6	∼25	∼50

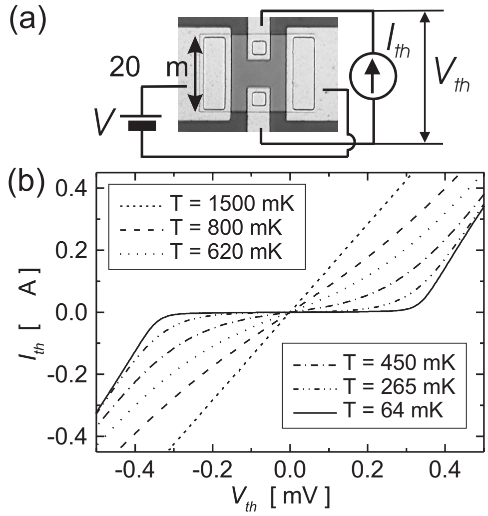

Fig. 1. (a) An optical micrograph of an S-Sm-S cooler and a schematic illustration of the connections to external circuitry in the measurements. (b) Current-voltage characteristics of the thermometer contacts ($3 \times 3 \mu m^2$) of S1F sample.

3. Resistance of the Schottky contact

The electrical resistance of a Schottky barrier formed at the interface between a normal metal and a semiconductor is very sensitive to the doping concentration in the semiconductor. The contact resistance can be characterised by the specific contact resistance $\rho_i (ohm \cdot cm^2)$. At low temperature and with high carrier concentration in the semiconductor (narrow barrier) the tunnel resistance is determined by field emission [8]:

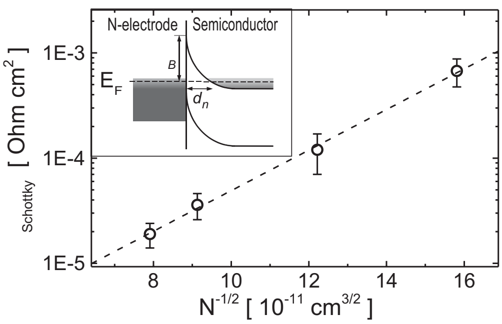

Fig. 2. The specific contact resistance ($\rho_{Schottky}$) as a function of carrier concentration for heavily doped Si. The dashed line corresponds to the equation $\rho = \rho_0 exp((N_0/N)^{1/2})$, with $\rho_0 = 5.8 \times 10^{-7} Ohm \cdot cm^2$ and $N_0 = 1.97 \times 10^{21} cm^{-3}$. Inset: Energy-level diagram for a metal-Schottky barrier contact on a heavily doped, degenerate, n-type semiconductor. The width of the depletion region is $d_n \sim (N_D)^{-1/2}$, Φ_B is the height of the barrier.

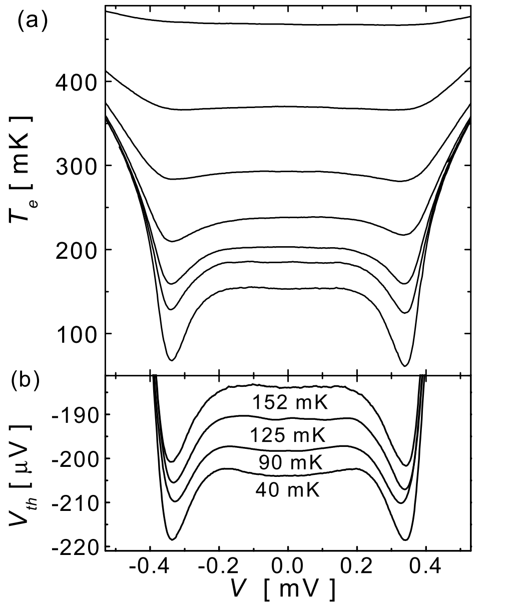

Fig. 3. The electron temperature (a) and the voltage across the thermometer junctions (b) as a function of the voltage across the S-Sm-S cooler structure with $N = 4.0 \times 10^{19} cm^{-3}$ at different substrate temperatures. Temperatures near to the curves correspond to the temperatures of the substrate.

$$\rho_i = \rho_0 exp(e\Phi_B/E_0), \quad (4)$$

where ρ_0 is a function of carrier concentration N, height of the barrier Φ_{B} and temperature. $E_0 \sim N^{1/2}$ is a characteristic energy of the tunneling process. The specific contact resistance of our cooler devices as a function of the $N^{-1/2}$ is presented in Fig. 2. The concentration dependence of the contact resistance is in agreement with Eq. (4).

4. Results and discussion

The maximum cooling of electrons in respect to the substrate temperature has been observed in the samples with $N = 4 \times 10^{19} cm^{-3}$. The electron temperature in silicon film as a function of the voltage across the S-Sm-S cooler for different substrate temperatures is shown in Fig. 3a. At temperatures below 450 mK all curves exhibit two clear minima at $V \approx 0.34mV$. For a structure with two junctions in series the maximum cooling power is obtained at $V \approx 2\Delta/e$, from there we get value of the gap for our $Al - 1\%Si$ film $\Delta \approx 0.17meV$. With decrease of the temperature the amplitude of the cooling peaks increases, which is due to the faster decrease of electron-phonon coupling than of the cooling power with decrease of temperature. Electron system cools to less than half the bath temperature below 150mK. Cooling was observed at all substrate temperatures down to 50 mK. The voltage across the S-Sm-S thermometer as a function of cooler voltage is presented in Fig. 3b for substrate temperatures below 150 mK, where electrons cool down to temperatures out of the thermometer calibration range.

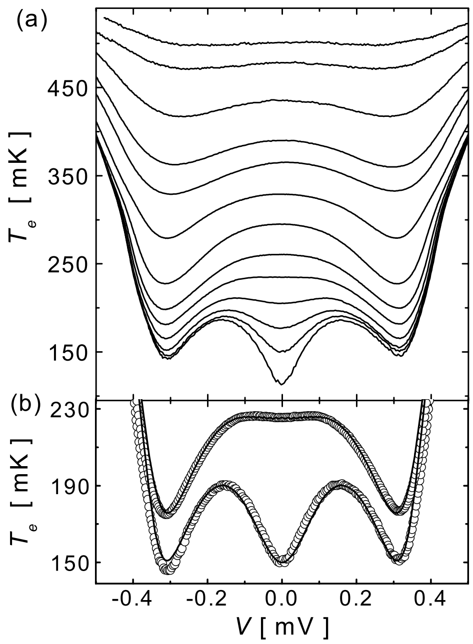

Fig. 4. (a) The electron temperature as a function of the voltage across the S-Sm-S cooler with $N = 6.7 \times 10^{19} cm^{-3}$ at different substrate temperatures. (b) Experimental data (dots) and results of the calculation of the electron temperature according to the model with a leak resistance in the junction ($R_{\mathrm{L}} = 7.8k\Omega$) for S1F at two different substrate temperatures.

The samples with higher carrier concentrations ($N \geq 6.7 \times 10^{19} cm^{-3}$) having lower characteristic resistance of the junctions and thus higher cooling power exhibit cooling only in the limited range of temperature. At low temperature the cooling curves demonstrate rapid increase of electron temperature with increase of the applied voltage in the sub gap region (Fig. 4). In spite of the high resistance of the silicon film (see Tab. 1) this behavior near zero bias can not be described by Joule heating in silicon: the electrical current in the sub gap region is too small to cause the observed heating effect. According to results of our numerical modeling the observed behaviour can not be described by back tunneling of hot quasiparticles and phonons [6]. The Joule heat produced by leak current through ohmic areas of the junction is more likely responsible for the overheating at lower temperature. Equivalent leak resistance (R_{L}) of the

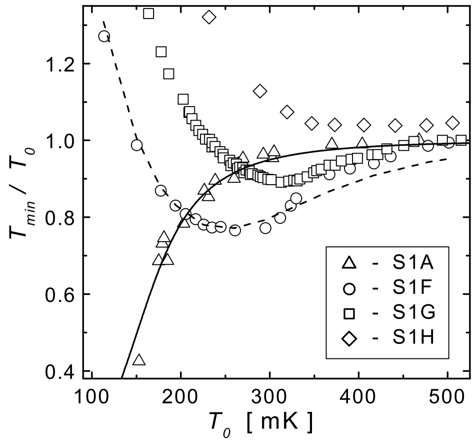

Fig. 5. The relative minimum electron temperature $T_{\rm min}/T_0$ as a function of the substrate temperature T_0 for coolers with different carrier concentration (triangles - $N = 4.0\times10^{19}cm^{-3}$, circles - $6.7\times10^{19}cm^{-3}$, rectangles - $1.2\times10^{20}cm^{-3}$, rhombi - $1.6\times10^{20}cm^{-3}$). The solid curve corresponds to a numerical solution of $P_{\rm max}+P_{\rm el-ph}=0$ with $\Sigma = 1.2\times10^8 W/K^5m^3$ and $R_{\rm T} = 750\Omega$. The dashed curve corresponds to the calculated $T_{\rm min}/T_0$ for S1F using the model with heating due to the leak resistance of the junction ($R_{\rm L} = 7.8k\Omega$).

$5 \times 18\mu m^2$ junction of S1F sample, derived from the comparison between measured and calculated $I - V$ characteristics, is about $7k\Omega$. The straight lines in Fig. 4b are results of the numerical calculation of the electron temperature for S1F according to the model of the heat balance in the cooler device [2,6], which takes into account Joule heating in the equivalent leak resistor connected in parallel to the junction and Joule heating in silicon, with following parameters: $\Delta = 0.17meV, R_{\rm T} = 90\Omega, R_{\rm L} = 7.8k\Omega, \Sigma = 1.5 \times 10^8 W/K^5m^3$. The good agreement between measured values and fitting parameters supports our conclusion that these heating mechanisms are responsible for the limitation of S-Sm-S cooler operation at lower temperature.

Relative minimum electron temperature $T_{\rm min}/T_0$ as a function of substrate temperature T_0 for coolers with different doping levels is presented in Fig. 5. In the case of S1A sample ($N = 4\times10^{19}cm^{-3}$) electron cooling increases with decrease of the temperature within the temperature range under investigation. Solid line in Fig. 5 is a fit of the experimental data with Eq. (3). The agreement between the experimental results and the fitting confirms that in the samples with low carrier concentration contribution of the different heating mechanisms is weak. The behaviour of $T_{\rm min}/T_0$ in the samples with higher carrier concentration is qualitatively different due to contributions of additional heating mechanisms. Dashed line in Fig. 5 is a calculated dependence for $T_{\rm min}/T_0$ versus T_0 (for S1F) based on the thermal balance in the film with additional terms corresponding to Joule heating in silicon film and in the equivalent leak resistor. In the cooler with carrier concentration $N = 1.2\times10^{20}cm^{-3}$ the heating of the normal electrode due to high resistance of silicon starts to play an essential role and limits cooling in the temperature range of the measurements. In the sample with the highest carrier concentration of $N = 1.6 \times 10^{20}cm^{-3}$ the cooling effect is fully suppressed by heating.

5. Conclusion

We have demonstrated cooling by semiconductor-superconductor structures with Schottky barriers at sub kelvin temperatures. The variation of the doping level significantly affects characteristic resistance of the junctions and performance of the cooler.

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References

[1] M. Nahum, T. M. Eiles, J. M. Martinis, Appl. Phys. Lett. **65** (1994) 3123.

[2] M. M. Leivo, J. P. Pekola, D. V. Averin, Appl. Phys. Lett. **68** (1996) 1996.

[3] J.P. Pekola, D.V. Anghel, T.I. Suppula, J.K. Suoknuuti, A.J. Manninen, M. Manninen, Appl. Phys. Lett. **76** (2000) 2782.

[4] A. Luukanen, M. M. Leivo, J. K. Suoknuuti, A. J. Manninen, J. P. Pekola, J. Low Temp. Phys. **120** (2000) 281.

[5] A. Bardas, D. Averin, Phys. Rev. B **52** (1995) 12873.

[6] J. Jochum, C. Mears, S. Golwala, B. Sadoulet, J.P. Castle, M.F. Cunningham, O.B. Drury, M. Frank, S.E. Labov, F.P. Lipschultz, H. Netel, B, Neuhauser, J. Appl. Phys. **83** (1998) 3217.

[7] A. M. Savin, M. Prunnila, P. P. Kivinen, J. P. Pekola, J. Ahopelto, A.J. Manninen, Appl. Phys. Lett. **79** (2001) 1471.

[8] D. K. Schroder, Semiconductor Material and Device Characterization, John Wiley & Sons (1990) 106.

[9] F.C. Wellstood, C. Urbina, J. Clarke, Phys.Rev. B **49** (1994) 5942.