BISTABILITY IN NbN HEB MIXER DEVICES

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ABSTRACT-All researchers working on THz HEB mixer devices are aware of the fact that the device is unstable in one part of its IV-curve. We have earlier reported that in this unstable region we observe relaxation oscillations at about 5 MHz for a number of devices in both the voltage and the current [1]. In this paper, we will present a quantitative model which describes the relaxation oscillations as well as some new transient measurements, which we will also report. As an HEB device is brought from the superconducting state through the critical current, it will enter a *bistable* state, which has been described for superconducting films in earlier papers and was reviewed in [2]. The bistable state means that two different states can potentially occur; a normal "hotspot" or "electrothermal domain", and the superconducting state. The theory in [2] predicts how the domain, once formed, may either expand, contract, or be in steady state, depending on the device current. The velocity with which the wall of the hotspot moves is also predicted. We propose a modification to the original bistability theory [2], taking into account the Andreev Reflection effect and the phonon specific heat. The relaxation oscillation frequency and the velocity of the hotspot boundary, for the conditions during the new measurements presented here, has been calculated according to the modified theory and the calculated results are within a satisfactory range in comparison with the measured data. Complete understanding of the role played by the movement of the hotspot boundary under various bias conditions (with and without LO power) for HEBs will require further measurements and theoretical work.

I. INTRODUCTION

We have reported in [1] measurements of an HEB device DC biased in the unstable region of its IV-characteristic. The measurement setup is shown in Figure 1. The devices were identical to devices which were used in our HEB mixer development program, with length 1μm and width 4μm. They were placed in a shielded box at the end of a "dipstick", which was inserted in a liquid helium storage dewar. We consistently recorded a repetitive waveform, in which we could distinguish two different frequencies. The device basically switched back and forth between a state in which it had a resistance, and its superconducting state, at a frequency in the range of several hundred kHz, which we will call the repetition frequency. Its value changed with the external circuit conditions such as the bias voltage or the external reactance. When the device was in the resistive state, we recorded a much faster oscillation with decaying amplitude, which we will call the relaxation oscillation frequency. The latter frequency was around 5 MHz. We found that the relaxation frequency was essentially the same for all devices we have measured, and insensitive to large changes in the external circuit. For example, low-pass filters with different cut-off frequencies were inserted in series with the DC bias supply. Thus we hypothesize that the relaxation oscillations are related to physical phenomena inside the device itself. Figure 2 shows the waveforms of both voltage and current of a 1μm long device. Observing the waveforms carefully we found that the maximum voltage across the device corresponds to the product of the average current and the normal resistance of the entire device. This implies that at the time when the peak voltage was recorded, the normal hotspot region covers the total length of the device. Thus we have reason to believe that the relaxation oscillation is due to the fact that the hotspot in the device changes its size periodically. If we assume that the resistivity inside the hotspot is equal to the resistivity of the NbN in its normal state, then the resistance of the device will vary periodically, and consequently the voltage across the device as well. We later found that in longer devices (5 and 10μm) the hotspot may not cover the entire length of the device. Its maximum size is proportional to the ratio of the peak voltage and the average current. The relaxation frequency of the longer device is somewhat lower than that of the short device because the hotspot travels longer in this case. A remarkable feature of these measurements is that the relaxation oscillations occur at a frequency (about 5 MHz) which is much lower than the frequency at which the device responds during mixing (in the low GHz range). Since movements of the hotspot boundary are likely to be important for modeling the device behavior in all of its possible states, we have continued to explore and measure the dynamic behavior of hotspots in NbN HEB devices.

In order to observe the hotspot boundary movement more directly, we performed a new set of pulsed measurements. Two pulse generators were inserted parallel to the DC bias supply in Figure 1. We investigated three ways of initiating the movement of the hotspot boundary by using the pulsed sources: 1) the device makes a transition from the superconducting state to the normal state ("fly-out"), 2) the device makes a transition from the normal state to the superconducting state ("fly-back"), 3) the size of the hotspot changes within the stable hotspot region. We concentrate on the fly back condition in this paper, and will only comment briefly on the other two cases, as well as the relaxation oscillations, at the end of the paper. The devices being used in this experiment are again phonon cooled NbN HEB devices similar to our mixer devices. The thickness of the film is 4nm, the width of the devices is 5μm, and the length of the devices is 1μm and 5μm, respectively. In the experiment, after we have applied two positive pulses the device is in the normal state; it is then transferred from the normal state to the superconducting (SC) state under a constant bias current. We find, in accordance with the theory which will be discussed in a later section, that the current has to be less than the minimum propagation current I_p, for the device to make this transition back to the SC state. We are able to calculate the propagation velocity of the hotspot boundary by analyzing the transient voltage and current waveforms. We reported an order of magnitude discrepancy between the theory and measured data on relaxation oscillations in [1]. Further details about the earlier measurements and the theory can be found in [3]. In this paper we propose that the original bistability theory needs to be modified by taking in account the Andreev Reflection and the phonon specific heat. The agreement between the modified theory and the measured data has been significantly improved.

II. EXPERIMENTS AND RESULTS

The experimental setup is similar to that in [1] except that we are using a current source instead of a voltage source. The device is first biased in the superconducting state. Then two positive current pulses are applied; the first one lasts about 75ns with an amplitude of 1.5mA, which generates a hotspot in the device; the second current pulse lasts about 2μs. Its amplitude is above the minimum propagation current I_P when combined with the bias current. The duration of the second pulse should be long enough so that the hotspot can expand and cover the entire device. After the second pulse ends, the device is biased only through the DC power supply, which is set to a value below I_P. The hotspot begins to shrink under this condition and finally disappears, and the device goes back to the superconducting state. The transient response of the voltage and the current of the device are recorded by a fast digital oscilloscope. Figure 3 shows the voltage and the current responses during this process. The voltage gradually decreases with time until it reaches zero, while the current stays at an intermediate value until the time when the voltage goes to zero, when it returns to the value set by the bias supply after a brief positive transient. We will try to explain this behavior in the next section. The same procedure was repeated for several different DC bias currents below I_P. The hot spot boundary velocity was calculated for the time period when the voltage changed linearly with time and the current was essentially constant, as marked in Figure 3. The velocity of the hotspot boundary can be calculated from the measured transient voltage and current waveforms as:

$$v = \frac{L}{2R_N}\frac{dV}{dt}\left[I(t)\right]^{-1} \tag{1}$$

where L is the maximum length of the hotspot, and R_N is the normal resistance of the entire device. The factor of 1/2 is used because there are two hotspot boundaries involved.

We find that the larger the difference between I_P and the measured average current is, the shorter time it takes for the device to go back to the superconducting state. Figure 4 shows the measured results (filled triangles) for the 1μm long device. We measured both 1μm and 5μm long devices and got similar results.

III. DISCUSSION

As shown in [1] and [2], when the bias current is less than the minimum propagation current (I_P) there is only one interception point between the curves of Joule heating (Q) and heat transport (W) as a function of temperature. This means that there is only one stable state in this case: the device will eventually go back to the superconducting state. The time needed for the device to go back to the superconducting state depends on the difference between Q and W. The device operating under a lower bias current will take a shorter time. As the voltage across the device decreases gradually, the current stays at an intermediate constant level, which is independent of the voltage, until the device becomes superconducting. Figure 5 shows the usual IV curve of the device, as well as the current when the voltage decreases from the stable hotspot region, based on our fly back measurement data. Note that this behavior is very similar to the hysteresis effect, which happens when decreasing the bias voltage in the IV curve from the left-most point in the stable hotspot region. The difference is that the device is still in the stable hotspot state when decreasing the bias voltage, and the current through the device at this time is the minimum propagation current I_p; during the fly back measurement, the device is instead in the transition state from the normal state to the superconducting state, and the current through the device must be less than I_p because the hotspot is shrinking. The current stabilizes at a new value slightly lower than I_P, but greater than the current imposed by the bias supply. In other words, the hotspot seems capable of self regulating the current, even in the dynamic state. We may designate this current I_P^{dyn}. The value of this current also depends on the current imposed by the bias supply, I_B. The lower I_B is, the lower is also I_P^{dyn} .

In order to fit the measured results to the bistability theory we need to calculate the normalized velocity with normalizing factor v_h, which is called the thermal velocity and is expressed as [1],[2]:

$$v_h = \frac{1}{C_e}\sqrt{\frac{2\lambda_e h}{kt}} \qquad (2)$$

where C_e is the specific heat of the electron system; λ_e is the lateral thermal conductivity of the NbN film; h is the heat transfer coefficient to the substrate; k is a constant, and t is the thickness of the film. The normalized velocity can now be calculated as in [1] and [2]. We find the measured velocity to be drastically lower than the theory based on the bulk thermal conductivity for NbN. We believe that the reason for this large discrepancy is that the value of v_h calculated in equation (2) is too high. In order to reduce v_h we propose that the theory needs to be modified by taking into account two effects: phonon specific heat and Andreev Reflection. Firstly, in the case of NbN films it is well known that the energy given off by the hot electrons to the phonons is not immediately transported to the substrate (the phonons effectively make a few "bounces" in the film before they can escape through the film/substrate interface). As the hotspot shrinks, and the film cools down from being normal at just above T_c (10 K) to being superconducting at 4.2K, energy must be released from the phonons as well as from the electrons. The evidence from the bandwidth studies [4] suggests that essentially the entire value of the phonon specific heat, C_p, should be added to C_e in equation (2). Secondly, Andreev Reflection must be considered when a current passes through a normal to superconducting interface. Figure 6 illustrates the process of Andreev Reflection. Assume that the Fermi energy is zero, and that the superconducting energy gap of the NbN film is 2Δ. An electron in the normal hotspot with energy less than Δ will be reflected back as a hole by the superconducting-normal boundary, while two electrons are transferred across the interface to form a Cooper pair, which adds to the superconducting Cooper pair condensate. Note that the Andreev Reflection preserves the current continuity. However, only charge is transferred, and no heat is transported across the interface. Thus the superconducting-normal interface acts as a perfect thermal isolator. Only the electrons with energy higher than Δ can transfer the heat. To obtain a first-order estimate[1] of the thermal conductivity across the interfaces, we assume that it is proportional to the fraction α_{th} of the incident electrons that can transport heat across the interface. This fraction can be calculated by multiplying the Fermi-Dirac distribution function, and a constant density of states (justified by the very small energy range), to find the electron density in the normal hotspot, n_E (E), and then integrating over the appropriate energy intervals [5]:

$$\alpha_{th} = \frac{\int_{\Delta}^{\infty} n_E(E)dE}{\int_{0}^{\infty} n_E(E)dE} = \frac{kT\ln\left(1+e^{-\frac{\Delta(T)}{kT}}\right)}{kT\ln 2} \tag{3a}$$

$$\Delta(T) = \Delta_0\left(1-\frac{T}{T_C}\right)^{\gamma} \tag{3b}$$

The exponent γ in (3b) is the same as in the expression for the temperature-dependence of

[1] A more accurate calculation would weight the electron density to yield the actual energy flow across the interface [6].

the critical current:

$$I_C(T,x) = I_C(0)\left[1 - \frac{T(x)}{T_C}\right]^{\gamma} \tag{4}$$

Here γ is chosen to be 1.0 to achieve the best fit with measured data for NbN devices on MgO substrates. As we apply a bias current to a device, the critical temperature of the film is partially suppressed by the current. We can use (4) to calculate an effective critical temperature, which we then use when performing the integral in (3a). Finally, after taking into account the phonon specific heat and the Andreev Reflection effect, the thermal velocity in equation (2) changes to:

$$v_h = \frac{1}{C_e + C_p}\sqrt{\frac{2\alpha_{th}\lambda_e h}{kt}} \tag{5}$$

Figure 4 shows the measured normalized hotspot boundary velocity vs. current, compared with calculations based on the modified theory (Eq. (5)). We adjusted the value of α_{th} to obtain a best fit between the measured data and theory. If we calculate α_{th} from (3a) we find a value which is about twice as large, as summarized in Table 1. Note that the latter calculation uses only measured parameters. Given the uncertainties in several parameters, and the error bars in the measurements, we believe that the agreement between theory and experiment is satisfactory. For example, a small adjustment of the parameter γ from 1.0 to 0.8 will produce much better agreement, as also noted in Table 1. We note that a similar measurement to the one reported here was performed by Freytag and Huebener [7]. These researchers measured Sn films and obtained agreement between theory and experiment without invoking Andreev reflection. The AR would have a much smaller effect in the case of Sn due to its smaller bandgap.

IV. CONCLUSION

In this paper the movement of the hotspot boundary when the HEB device makes transitions from the normal state to the superconducting state has been successfully measured. The measurement results fit the theory quite well after taking into account the phonon specific heat and Andreev Reflection effect. It is quite clear that under the conditions of this particular measurement the hotspot boundaries move very slowly, compared with the thermal response time of the device as a mixer. We also found an additional interesting phenomenon: the device is able to stabilize the current during the dynamic transient response. We want to briefly comment on the results of other experiments which we have done so far. When we triggered the device with a pulse to make a transition from the superconducting state to the normal state, we found an even slower velocity than measured here (for a given value of $I-I_P$). It is possible that during this transition, during which the device is in a strong negative resistance state, further nonlinearities play a role. Measured pulse response when the device moves from one stable hotspot state to another (either with or without applied LO power) appears faster than the process described in this paper, based on preliminary measurements. However, we must improve the detection speed of our measurement system in order to confirm this. The relaxation oscillation frequency is predicted very well (within a factor of two) based on our modified model. In order to fully understand the mechanism of the hotspot boundary propagation more experiments clearly need to be performed and interpreted under different conditions.

V. ACKNOWLEDGEMENTS

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REFERENCES

[1] Y. Zhuang and S. Yngvesson, "Detection and Interpretation of Bistability Effects in NbN HEB devices", 13th Intern. Symp. Space THz Tech., pp.463-472 (2002).

[2] A.VI. Gurevich and R.G. Mints, "Self-Heating in Normal Metals and Superconductors," Rev. Mod. Physics, **59**, pp. 94-999 (1987).

[3] Y. Zhuang, "Linear and Nonlinear Characteristics of NbN Hot Electron Bolometer Devices," Ph.D. Thesis, Dept. of Electrical and Computer Engineering, University of Massachusetts at Amherst, Sept. 2002.

[4] S. Cherednichenko, P. Yagoubov, K. Il'in, G. Gol'tsman, and E. Gershenzon, "Large Bandwidth of NbN Phonon-Cooled Hot-Electron Bolometer Mixers on Sapphire Substrates", 8th Intern. Symp. Space THz Tech., pp. 245-257 (1997).

[5] H. Merkel, "A Hot Spot Model for HEB Mixers Including Andreev Reflection", 13th Intern. Symp. Space THz Tech., pp. 53-64 (2002).

[6] H. Merkel, priv. comm..

[7] L. Freytag and R.P. Huebener, "Temperature Structures in a Superconductor as a Nonequilibrium Phase Transition," J. Low Temp. Physics, **60,** 377 (1985).

Table 1: Comparison of the AR factor α_{th} between the measurement and the calculation

Length(μm)	1	5
α_{th} (Measure)	0.08	0.12
α_{th} (Calculate) for γ= 1	0.18	0.21
α_{th} (Calculate) for γ= 0.8	0.10	0.11

FIGURES

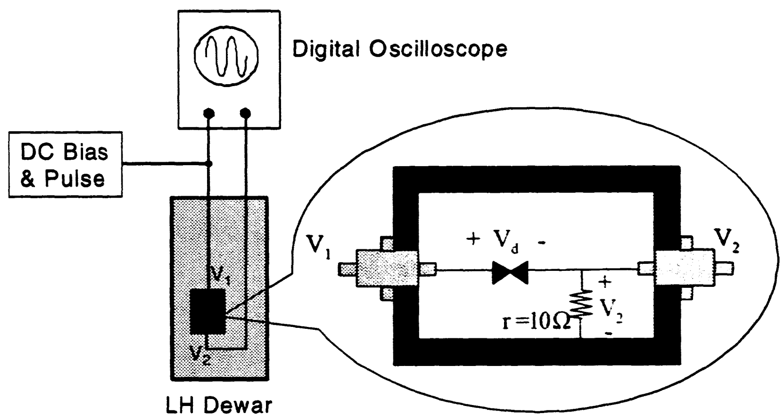

Figure 1: Experimental setup for the bistability measurement

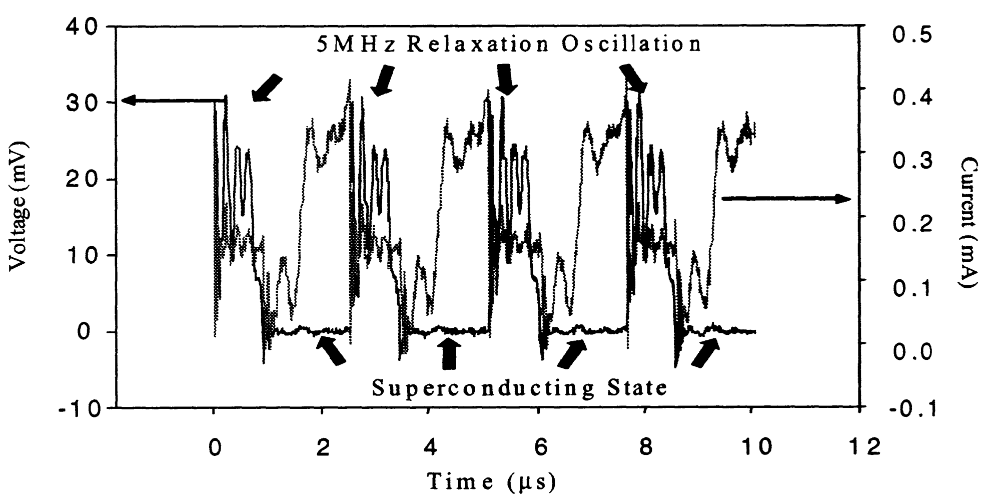

Figure 2: Voltage and current waveform in the bistability region of the HEB device

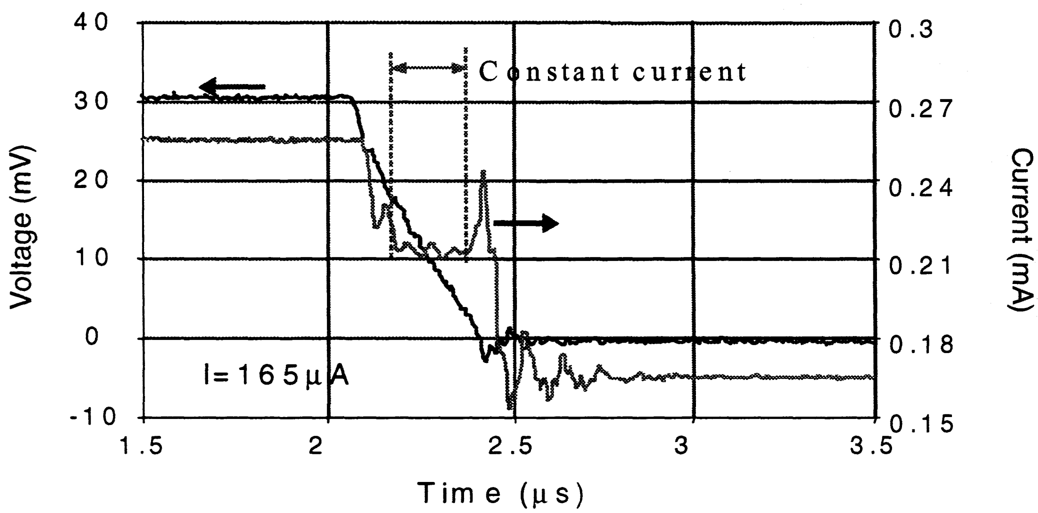

Figure 3: Voltage and Current waveform in the fly back measurement with bias current I=165µA

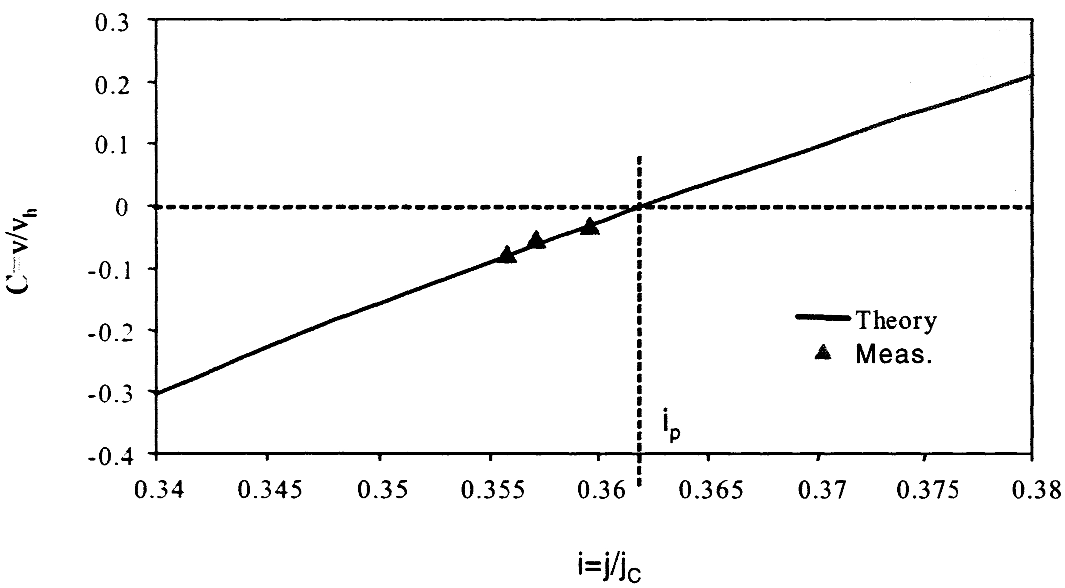

Figure 4: Comparison of normalized propagation velocity of the hotspot boundary between the measurement and the modified bistability theory

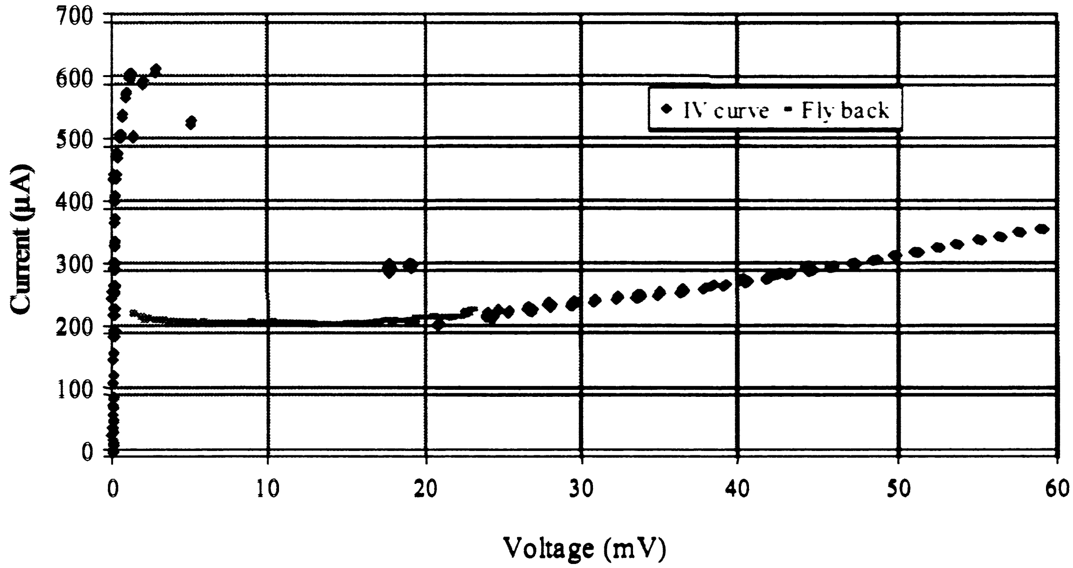

Figure 5: IV curve from DC bias supply and IV relation from fly back measurement

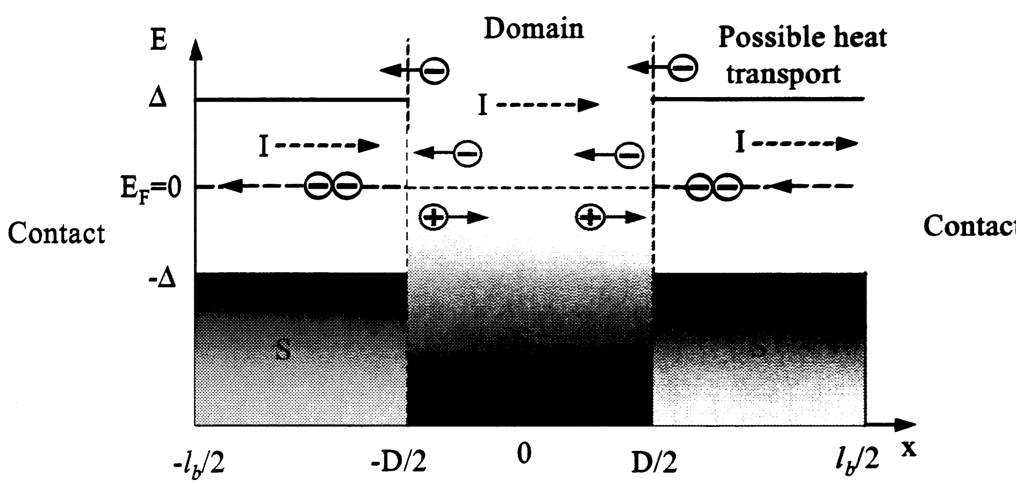

Figure 6: Andreev reflection and possible heat transport in an HEB device