Negative Resistance Effects in NbN HEB Devices

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ABSTRACT -It is well known that HEB devices, whether phonon-cooled or diffusion-cooled, exhibit unstable regions of their IV-characteristics. These phenomena occur when the device is not pumped by the LO, or when the LO power is decreased sufficiently compared with the power level required for optimum operation. The bias voltage is between the critical value at which the device stops being superconducting, and the point where a stable hotspot is formed. We have studied the instabilities occurring in un-pumped NbN devices that are also being used in our THz mixer receivers. The aim is to understand the physical processes, which produce the instabilities in the device under these conditions. Eventually, this should also be useful for understanding the device models in the LO-pumped regime. Whereas other researchers have reported sidebands of the IF in diffusion – cooled devices, we find that a variety of different frequencies and waveforms may be produced in the NbN devices, with frequencies varying from about 300 Hz to several hundreds of MHz. A typical range is a few hundred kHz, however. During our measurements the device is mounted on a circuit board and enclosed in a small box in order to present well – defined circuit conditions. We then add chip components to the circuit and study the effect these have on the instabilities. We have identified some conditions for which the device is stabilized, which may be useful in practical mixer applications, and also present in this paper preliminary results for a model which can be used to interpret the physical processes which occur in the devices. In this model the device is in a metastable hotspot state in which heating and cooling recur periodically.

I. INTRODUCTION

The theory of NbN Hot Electron Bolometric (HEB) Mixers has primarily been based on the "standard model" in which the device is regarded as a point bolometer[1]. Newer models extend the treatment to one or two-dimensional bolometers [2,3], and have contributed toward a more complete understanding of these new devices. Our new approach to this question is to observe the NbN HEB mixers' behavior when the device is biased in the instability region, in which the device shows negative dynamic resistance, and to present a possible model to interpret the experimental data obtained in this region. Studying the negative resistance effects in HEBs is important in understanding how to optimize the bias circuit for the device's best performance, how to protect the device and achieve a long lifetime, and how to model the device, especially vortex phenomena.

In the superconducting state the current through the device increases with applied bias voltage until it exceeds the critical current I_C, whereupon the device makes a transition from the superconducting state to the resistive state at a voltage of a few mV and a lower current. Since the voltage increase is associated with a decrease in current, this transition thus represents a negative differential resistance. By adjusting the bias voltage to values between these two states, we find a region of the I – V curve in which the device is potentially unstable due to the negative resistance. We can observe periodical or quasi – periodical waveforms on an oscilloscope with frequency components typically ranging from about 100 kHz to 6 MHz, and in some cases considerably lower (300 Hz) or higher (hundreds of MHz).

II. EXPERIMENT AND RESULTS

The device was fabricated from a sputtered 3.5nm NbN thin film on a silicon substrate, and was integrated with a log – periodic antenna [4]. The critical temperature of the film is 10.5K. Fig. 1 shows the experimental set up. The device was mounted on a circuit board in a small metal box to reduce the outside radiation interference, and then connected to a semi – rigid coaxial cable, which was built into a dipstick used to insert the device into a liquid helium dewar. The bias voltage was applied to the device through a low pass filter and the coax. The oscillation frequency was observed by a Tektronix 11403A digitizing oscilloscope.

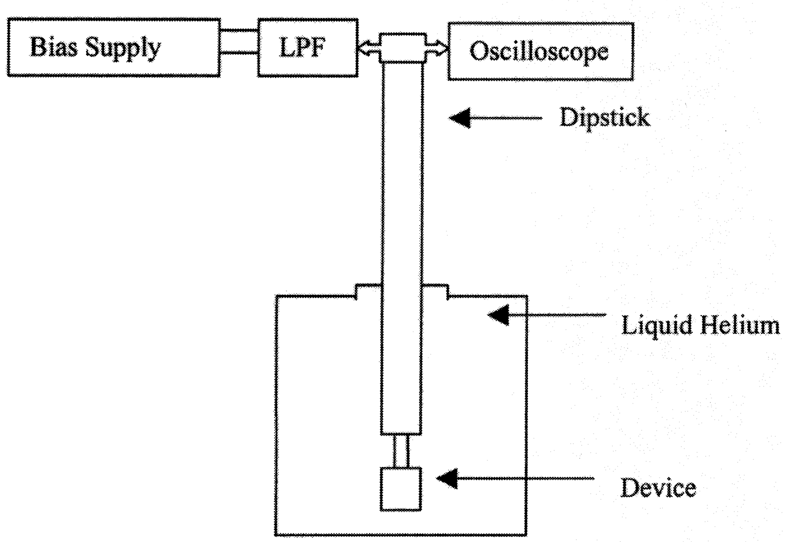

Fig. 1: Experimental set up for the HEB negative resistance study

There are five different regions in the typical I – V characteristics as shown in Fig. 2. The entire device is superconducting in region (1), reaching a critical current, I_{CS}, at which the current drops and instabilities of different kinds can be observed. First, slow jumps occur in region (2), which are picked up directly by our Labview I – V recording system. We have found that the jumping frequency depends mainly on the opamp circuit in the bias supply, and can be as slow as 300 Hz. Quite large amplitude oscillations occur in this region. A stable hotspot occurs in region (4), which will expand gradually with the bias voltage until the whole film goes normal. LO power is applied in region (5). The current through the device is then suppressed to a lower level. In between regions (2) and (4) is region (3), in which the recorded DC current and voltage are relatively stable, and oscillations can be detected on an oscilloscope. We believe the oscillation frequencies in region (3) are related to both the physical characteristics of the device, and to other

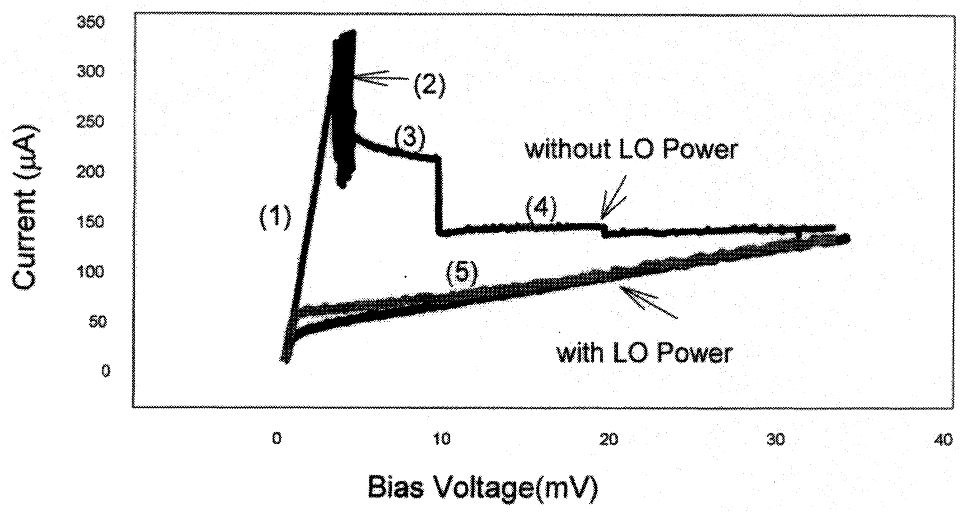

Fig. 2: Typical I – V Characteristics of NbN HEB Device

components connected to it, and our HEB negative resistance study is focussed on this region. From stability theory a network is stable if the real part of the impedance is greater than zero; thus it is possible to stabilize the HEB device in its negative resistance region by inserting a series resistor in the circuit, as shown in Fig. 3. R_S is the internal resistance of the bias supply, which is very low due to a feedback circuit. R_{STAB} is the series – stabilizing resistor. Increasing R_{STAB} will eventually make the circuit stable. There will be no oscillations detected after the circuit is stable. We tested several devices, and the measured R_{STAB} value ranges from 6Ω to 20Ω. Fig.4 shows the I – V characteristics after inserting the stabilizing resistor. The I – V curve without the stabilizing resistor is also included in order to provide a comparison. Based on this simple model we can conclude that the negative resistance of the HEB devices we tested is around -6Ω to -20Ω.

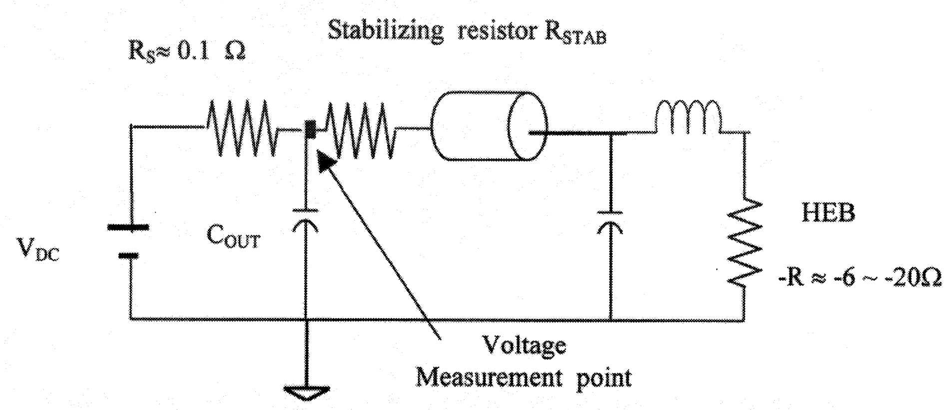

Fig. 3: HEB measurement circuit diagram after inserting stabilizing resistor

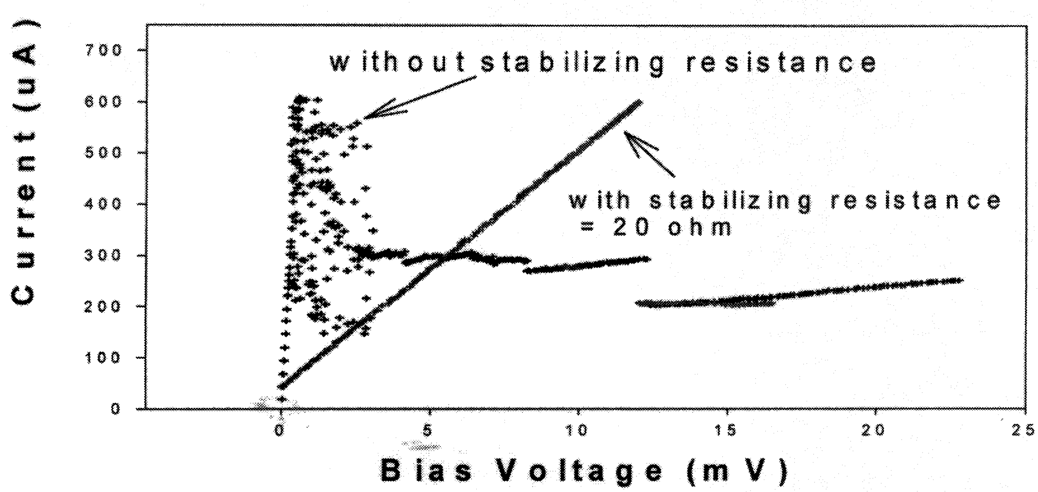

Fig. 4: I – V Characteristics of HEB Device with stabilizing resistor

Typical oscillation waveforms measured in region (3) are shown in Fig. 5. The bias point at which the measurements were made is shown in Fig. 7. The current measurement was done by measuring the voltage across a series resistor inside the bias supply, which doesn't affect the internal resistance of the supply. Fig. 5(a) shows that the voltage periodically has sharp spikes with relaxation oscillations that almost die out before the next spike comes. The repetition rate of the spikes is about several hundred kHz. It increases with the bias voltage, and can also be decreased by adding some series inductance. Fig. 5(b) is the corresponding current waveform. The current drops a little bit

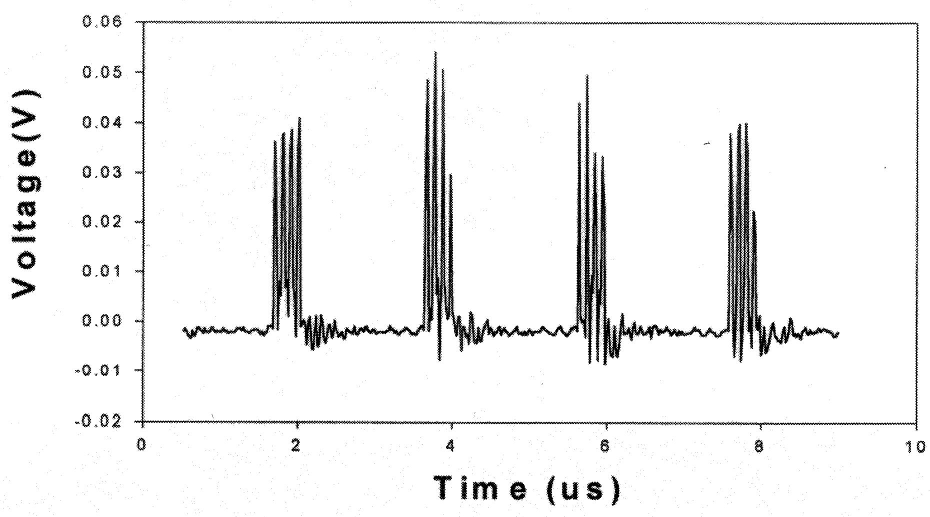

Fig. 5(a)

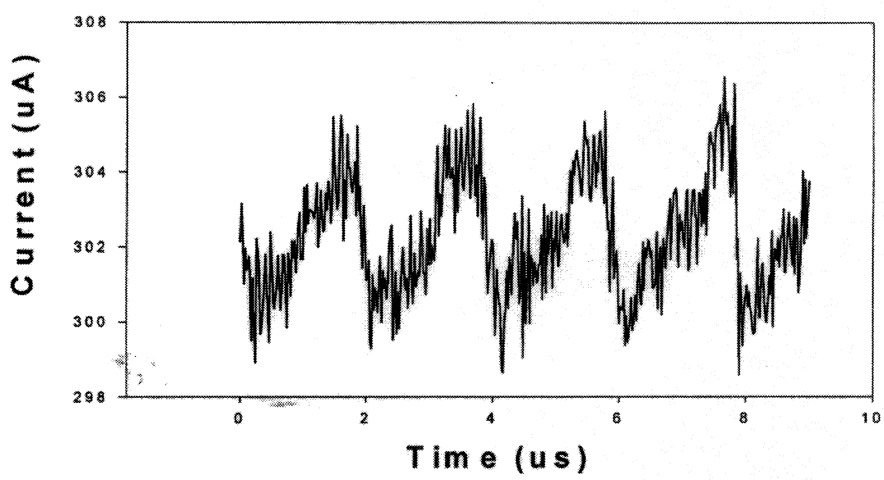

Fig. 5(b)

Fig. 5: (a): Voltage waveform in region (2); (b): Current waveform in region (2)

as the voltage spikes occur, and then recovers with a relatively longer time constant as the voltage spikes die out. The percent change in current is only about 1%. The device was also measured with a microwave vector network analyzer from 300 kHz to 400 MHz, and showed a *positive resistance*, essentially independent of frequency over this range (Fig. 6). The measured microwave resistance is equal to the average DC resistance, as shown

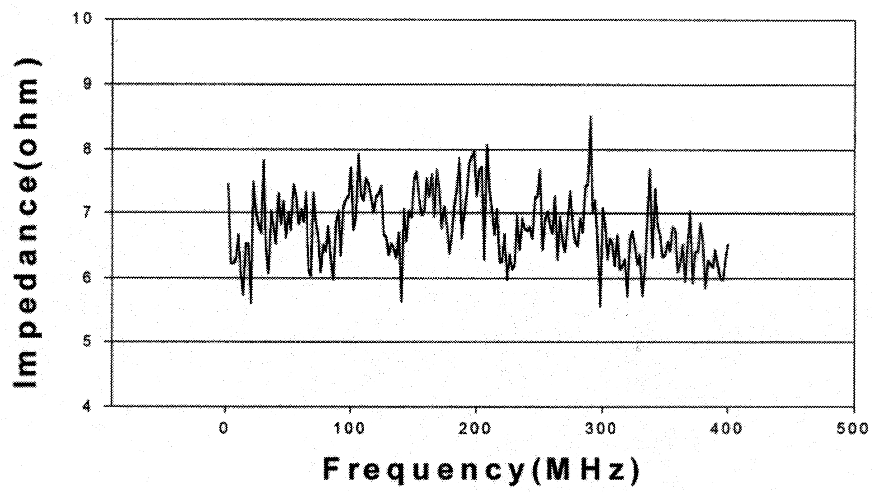

Fig. 6: Impedance of HEB device measured from network analyzer

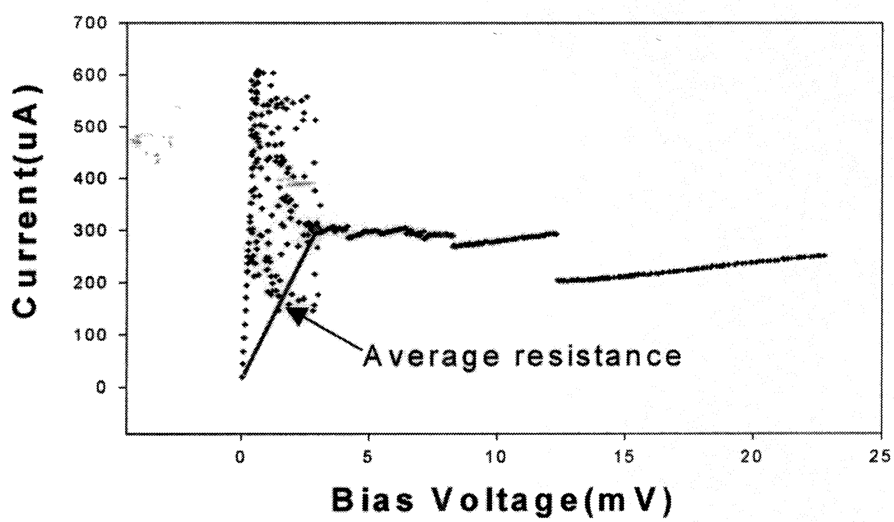

Fig. 7: Average resistance of HEB at the operating point during ANA measurement

in Fig. 7. It follows the DC resistance of the bias point as the bias voltage is increased. The simple negative resistance model we used above cannot explain this behavior – it would predict that the network analyzer should measure a *negative resistance* value. Instead, we will introduce a version of the hotspot model which is related to the one – dimensional models studied by Merkel et al [2,3]. Fig. 5 clearly indicates that most of the time both the voltage and the current are stationary, and thus the device resistance is essentially constant: the current only changes by 1%, and the voltage is constant except for a brief interval when the voltage spikes are detected. We believe that the device is heated or cooled periodically due to the negative resistance effect, and correspondingly the hotpot expands or shrinks at the same rate. Thus, the hotspot formed in region (3) is different from that in region (4), where the hotspot is stable with a length determined by the bias voltage. We will introduce the term "*metastable hotspot*" to describe the device in region (3), and will expand further on this idea in section III. The clearest evidence for this model is furnished by the network analyzer measurements, which indicate that the average resistance is positive. The instability represented by the negative resistance effect is then limited to the brief interval when the voltage spikes occur. The voltage spikes are not seen by the network analyzer, partly because they are at a too low frequency to pass the bias tee of the ANA, and partly because the phase detector of that instrument will not detect them.

III. DISCUSSION

We now discuss our interpretation of the measured results in terms of a one – dimensional hotspot model.

The superconducting state

First, in **region (1)** the device is superconducting and the magnetic field associated with the current begins to penetrate the NbN film, forming a number of vortices. This is typical of all type II superconductors. The fact that we do not detect a voltage indicates that the vortices are not moving; they are pinned by defects in the film. At the critical current (I_{CS}, the critical current in the superconducting state) the Lorentz force between the current and the magnetic field exceeds the pinning force, and the vortices move transverse to the film, inducing a voltage. The voltage dissipates power which heats the film, increasing its resistance and decreasing the current. This represents the basic negative resistance effect.

The metastable hotspot state

Skipping region (2) for a moment, **we will now discuss region (3).** The suggested first order model for the metastable state in this region is shown in Fig. 8. Refer to Fig. 5 for the voltage and current versus time. In the middle of the device there is a metastable hotspot with electron temperature $T_e > T_c$, and with vortices located outside of it. After the initial decrease in current the vortices will again be pinned since the Lorentz force has decreased. The device has a resistance due to the hot spot shown in the figure. Less power is also being dissipated, and the current rises again. When the current reaches a new and lower critical current I_{CM} (critical current in the metastable state) the vortices begin to move again, which gives rise to the voltage spikes. The device is then again heated. The hotspot expands slightly, but there is not enough heating power to complete the process and form a stable hotspot as in region (4), so the voltage spikes die out. The device then begins to cool down, and the hotspot decreases in length. The resistance reduction causes the current to increase until it reaches I_{CM} again. This model then shows that the voltage and current are close to the metastable bias point, except for the brief voltage spikes. It appears reasonable to assume that the heat transfer equations of the hotspot model [2,3] have metastable solutions of the above type. Further theoretical explorations of this model will have to be pursued to prove this point, however.

Critical current

The average current **in region (3)** (about 300 μA, see Fig. 4) is roughly equal to the critical current under the conditions which correspond to a hotspot in the middle of the device, since the measured current only oscillates by 1 %. It is well known that the critical current decreases with the temperature. As shown in [2,3] the electron temperature T_e close to the hotspot is a little less than the critical temperature T_c, and therefore the critical current (I_{CM}) is less than that when the device goes from the superconducting state to the unstable state (I_{CS}). The latter critical current has a higher value (600 μA, Figure 4) since the entire device is at a lower temperature (4.2K) in this case.

Voltage dependence of the repetition frequency

The voltage spikes appear to produce about the same amount of heating each time, independent of the bias voltage. This is consistent with the fact that the current (and not the voltage) determines the density of the vortices, as well as the Lorentz force they are exposed to; note that the current is observed to be roughly constant in region (3). The cooling effect produced by the hotspot, however, is proportional to the area of the hotspot (the cooling is due to phonons emitted from the film through the film/substrate interface). As the bias voltage increases, the hotspot expands, and it is then able to remove the heat produced by the voltage spikes faster. Therefore, the current reaches I_{CM} faster, and the repetition rate of the periodic heating and cooling cycle increases, as observed.

Effect of the stabilizing resistor

We can now also explain the effect of the stabilizing resistor in terms of the metastable hotspot model. Without a stabilizing resistor we have a fairly wide range in voltage over which the unstable state occurs. We finally reach **region (4)**, and a stable hotspot, when the hotspot is large enough to produce sufficient cooling to take care of the extra heating periodically produced by the vortices (see Fig. 4). If we insert a sufficiently large stabilizing resistor in series with the bias source, then when the current reaches I_{CS}, the voltage is large enough to produce a hotspot which is again large enough to cool the device, and prevent the heating due to the vortices from recurring periodically.

Effect of the external circuit

The repetition frequency of the waveforms shown in Fig. 5 can be decreased if an inductance is added in series with the bias supply. With other circuit configurations, we have recorded oscillations which were more sinusoidal, down to about 300 Hz, and as high as several hundred MHz. The oscillations in **region (2)** also tend to be more sinusoidal.

Instabilities in an LO-pumped device

At the previous Space THz Technology Symposium, sidebands on either side of the IF frequency were reported, when recording the output of diffusion-cooled HEB mixers on a spectrum analyzer [5]. The sidebands occur when the IV-curve shows a negative slope (or a close to zero slope). We believe that these sidebands are related to the type of oscillations we have recorded through the bias line.

In terms of the hotspot model, there should be a continuous transition from a stable hotspot state when sufficient LO power is applied, to the unstable region, as the LO power is decreased. We will extend our studies to this transition in future work. We will design an improved bias circuit for the NbN mixer based on the new data presented here. Vortices should occur in the stable hotspot state as well, and a comparison of the hotspot models in regions (3), (4) and (5) should be illuminating in regard to the performance of THz NbN HEB mixers in general.

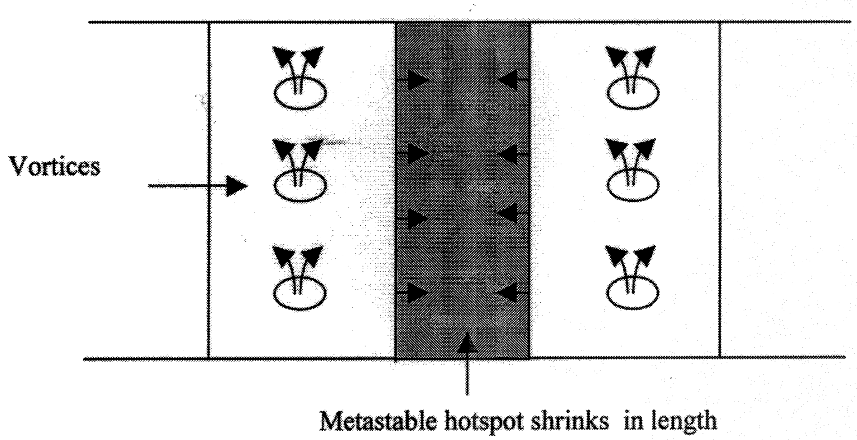

Fig. 8: Suggested first order model for the metastable state

IV. CONCLUSION

In this paper we have studied un – pumped NbN HEB devices in the instability region. Inserting a series resistor can stabilize the devices. The negative resistance of the tested devices is around – 6Ω to – 20 Ω. Measured voltage and current waveforms in the instability region imply that the devices exist in a metastable state in which the unstable hotspot expands or shrinks periodically at the device is heated or cooled. This preliminary first order model was used to interpret the experimental data.

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