GAIN BANDWIDTH AND NOISE TEMPERATURE OF NbTiN HEB MIXER

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Abstract

We have determined that the gain bandwidth of phonon-cooled HEB mixer employing NbTiN films deposited on MgO layer over Si substrate is limited by the escape of phonons to the substrate. The cut-off frequencies of 1 μm long devices operating at $T \cong T_c$ based on 3.5 nm, 4 nm and 10 nm thick films amount to 400 MHz, 300 MHz, and 100 MHz, respectively. The gain bandwidth of 0.13 μm long devices fabricated from 3.5 nm thick film is larger and amounts to 0.8 GHz at the optimal operating point and to 1.5 GHz at larger bias. The increase of the gain bandwidth from 400 MHz up to 1.5 GHz with the change of bridge length is attributed to diffusion cooling. A double sideband noise temperature of 4000 K was obtained for heterodyne receiver utilizing pilot NbTiN HEB mixer (not optimized for normal state resistance) operating at the local oscillator frequency of 2.5 THz.

Introduction

Recently superconducting NbTiN thin films have aroused much interest as a promising basis for HEB mixer technology. The sensitivity and the required local oscillator power of HEB mixers employing this material [1] are rapidly approaching the level of NbN phonon-cooled HEB mixer, which is the best candidate now for heterodyne receivers operating at frequencies well above 1 THz. The gain bandwidth of HEBs based on NbTiN is still well below the value needed to fit the requirements of currently developed projects [2]. In this work, we have studied gain bandwidth of the devices based on NbTiN thin films at 0.14 and 0.9 THz local oscillator (LO) frequencies and noise temperature of the heterodyne receiver employing NbTiN HEB mixer operating at 2.5 THz LO frequency. As a result of these measurements, we have determined the main physical process which limits the gain bandwidth of our devices. We have also compared the sensitivity of pilot NbTiN HEB mixer with the sensitivity of NbN HEBs at that high LO frequency.

In practical operation, the electron subsystem of the device is heated up to the optimal operating point by applying DC and LO power, while the physical temperature of the device stays low. Under these conditions, the HEB mixer shows the best noise performance, but the physics of its operation is complex, most of all due to the non-uniform distribution of the electron temperature along the bridge. The cut-off frequency of the device in this regime is determined not only by phonon cooling, but also by electro-thermal feedback, Andreev reflections, diffusion of hot electrons, spatial variations of critical current along the bridge, and so on. It is difficult to estimate the influence of each factor separately. In the case of uniform electron temperature distribution along the bridge, the physics of the device operation can be described by simpler equations, and the mixer's cut-off frequency is completely determined by several characteristic times [3]. The values of these characteristic times can be obtained from the dependence of gain bandwidth on temperature and film thickness. Practically, the distribution of electron temperature is uniform along the bridge if LO and DC powers are small and electron effective temperature is equal to T_c and, in its turn, to the physical temperature of the device.

The operating point can be reached either by increasing the temperature up to the transition value, or by applying magnetic field that would decrease T_c to the physical temperature. There are two main processes determining the gain bandwidth of phonon-cooled HEB mixer for this regime. First, the energy is transmitted from hot electrons to the lattice via inelastic scattering of electrons with phonons. Thermal equilibrium between electron and phonon subsystems is established during phonon-electron interaction time $\tau_{ph-e} = \tau_{e-ph}c_e/c_{ph}$. Here c_e and c_{ph} are, respectively, electron and phonon specific heats, τ_{e-ph} is electron-phonon interaction time which depends on temperature as $\tau_{e-ph} = \alpha T^{-\beta}$, where α and β are certain constants determined by the film material. The specific heat of the phonons at temperatures close to typical value of T_c has the same order of magnitude as the electron specific heat, and therefore the escape of non-equilibrium phonons to substrate influences the energy relaxation process. The escape of non-equilibrium phonons to the substrate can also be described by the characteristic time τ_{esc}. In the case of uniform heating, the cut-off frequency of HEB mixer is mostly influenced by the largest of these time constants [3] if the bridge length is greater than thermal healing length $L_{e-ph} = (D\tau_{ph})^{1/2}$ [4]. In this equation, τ_{ph} is the hot electron bolometer's time constant if the diffusion cooling is neglected, D is the diffusivity of electrons in the superconducting bridge.

When the bridge length is about L_{e-ph} or smaller, the diffusion cooling contributes to the cut-off frequency of the device. The gain bandwidth of HEB mixer with bridge length that is much shorter than L_{e-ph} is determined only by diffusion cooling. For intermediate bridge lengths, both the diffusion cooling and the phonon cooling should be considered.

In this work, we have studied several NbTiN HEB mixers. The analysis of the dependence of 1 μm long mixer's cut-off frequency on temperature and film thickness at $T = T_c$ allows us to determine the physical process which limits the phonon-cooling rate. It is the escape of non-equilibrium phonons from the film to the substrate. The gain bandwidth of 0.13 μm long devices operating at a low temperature is larger than for the 1 μm long ones. This could be explained if the diffusion cooling is considered. In order to verify this assumption, the diffusivity of electrons in NbTiN films has been measured. The noise performance of practical NbTiN HEB mixers has been tested in a 2.5 THz heterodyne receiver.

Device design and fabrication

The HEB mixers are manufactured from superconducting NbTiN film on silicon substrate with 200 nm thick MgO buffer layer deposited by e-beam evaporation. The 3-4 nm and 10 nm thick NbTiN films are deposited by DC reactive magnetron sputtering of NbTi composite target in Ar and N_2 mixture. The Ar partial pressure is 3.2×10^{-3} torr, and the N_2 partial pressure is 1.2×10^{-4} torr. With discharge current and voltage amounting to 1 A and 300 V respectively, a sputtering rate of 0.5 nm/s is obtained. During the deposition the substrate is heated up to 600 ^{0}C. The typical film transition temperature T_c is 11 K for 3-4 nm thick films and 13 K for 10 nm thick NbTiN film. Transition width amounts to 0.3-0.5 K for NbTiN films of both thicknesses. The film transition temperature decreases during the device fabrication.

The films are patterned using e-beam and photolithography to form 2.4 μm wide and 0.13 μm long structures for investigation of noise temperature of heterodyne receiver employing NbTiN HEB mixer, and 10 μm wide and 1 μm long structures for studying mixer's gain bandwidth at a physical temperature close to T_c. Devices made for noise measurements are fabricated from 3.5 nm thick NbTiN films on MgO buffer layer over Si substrate by lift-off electron-beam lithography and lift-off photolithography. The 0.13 μm long mixer element is formed by lift-off e-beam lithography across two overlaid Ti-Au-Ti (Ti ~ 3 nm, Au ~ 30 nm, Ti ~ 10 nm) small contact pads, and the 2.4 μm width is formed by using a SiO mask made by e-beam lithography as well. The central part of the self-complementary spiral antenna is formed using lift-off e-beam lithography based on Cr-Au metallization (Cr ~ 3 nm, Au ~ 200 nm). Next, the outer part of the mixer is made by lift-off photolithography based on Ti-Au-Ti metallization (Ti ~ 5 nm, Au ~ 200 nm, Ti ~ 20 nm). The normal resistance of the typical device is 20 Ω. Contact resistance also contributes to this value, and the resistance of the bridge itself is slightly less than 20 Ω.

The devices developed for investigation of phonon cooling in NbTiN HEBs at $T \cong T_c$ are much larger in-plane (10 μm wide and 1 μm long) than the previous ones, and are fabricated from 3.5, 4.2 and 10 nm thick NbTiN films on MgO buffer layer over Si substrate. This design allows us not to use e-beam lithography for fabrication process, and the spiral antenna is formed using direct photolithography. Physically, this design increases the volume of superconducting bridge, which, in turn, increases the dynamic range of the device. The device noise temperature increases with an increase of physical temperature. At temperatures close to T_c, the sensitivity of HEB mixer is rather low. This fact along with small dynamic range of practical device makes it impossible to perform heterodyne measurements at $T = T_c$ for 2.4 μm wide by 0.13 μm long devices.

The last process for both designs is the removal of the NbTiN layer by ion milling in Ar atmosphere from the whole substrate surface except the central part of spiral antenna which was protected by SiO or resist masks.

Experimental setup

The noise temperature of quasioptical heterodyne receiver employing NbTiN mixer at 2.5 THz LO frequency was measured at the Institute of Space Sensor Technology and Planetary Exploration, DLR, in collaboration with Alexei Semenov and Heinz-Wilhelm Hubers. The experimental setup is described in [5].

The experimental setup for measurements of the output power versus IF at 0.9 THz LO frequency is presented on Fig. 1. Radiation from two backward wave oscillators (BWOs) operating within the frequency range of 0.87–1 THz is superimposed by Maylar beam splitter and arrive into liquid He-cooled vacuum cryostat through a Teflon window. Terahertz radiation is coupled to the mixer via a hybrid antenna, an extended hemispherical Si lens along with a planar spiral antenna integrated into the device. The device under test is glued to the flat side of the lens. A bias tee is used to feed bias to the device and to pass the output signal at an intermediate frequency to the room temperature amplifier chain. The amplifier chain has a gain of approximately 70 dB and operates within frequency ranges of 0.1-2 GHz, 0.7-4 GHz, and 3.5-8 GHz. The value of the intermediate frequency is monitored using spectrum analyzer inserted in the chain via a –20 dB directional coupler. The output power is measured using power meter.

The mixer's output power as a function of intermediate frequency is measured at the 140 GHz LO frequency. The radiation from two BWOs is superimposed by Maylar beam splitter and arrives into dipstick with vacuum chamber through a Teflon window. It passes the oversized waveguide and is coupled to the device via a horn antenna. To the end of horn antenna a massive copper plate is soldered, to provide enough space for attached thermometer and for framing an appropriate coupling between a device and the IF chain. The temperature is kept near the transition point value of the device under test by applying DC power to the heater. The heater is mounted on the horn antenna far from the device to provide an almost uniform temperature along copper plate. Output signal passes through a 50 Ohm coaxial cable to a room temperature bias tee used for applying bias voltage to a device. Then the output signal is amplified using a room temperature amplifier chain and is monitored by a power meter. One of the BWOs is tuned to change intermediate frequency and its power is maintained at a constant level by a grid attenuator. The power of both BWOs is kept at low level to ensure that the effective electron temperature stays close to the physical temperature of the device. Thus, a chopper is inserted into the path of the tuned BWO, and the RF power is observed by recording the direct response voltage of the bolometer using a selective nanovoltmeter.

Experimental results

The double sideband (DSB) receiver noise temperature of a heterodyne receiver employing NbTiN HEB mixer is measured by Y-factor method. The receiver shows 4000 K noise temperature at LO frequency of 2.5 THz. The best noise performance of the mixer is obtained at the operating point marked on Fig. 2 as point 1. At much larger bias voltage the noise performance is worse but the gain bandwidth is larger. One of such operating points is marked on Fig. 2 as point 2.

The gain bandwidth of a 0.13 μm long device is measured at 0.9 THz LO frequency at two different operating points mentioned above. The device shows the gain bandwidth of 0.8 GHz and 1.5 GHz at operating points 1 and 2 respectively. Obtained dependencies of output power versus IF are presented on Fig. 3

The cut-off frequencies for the devices based on 3.5, 4.2 and 10 nm thick NbTiN films deposited on MgO buffer layer over Si substrate are measured using the experimental setup with BWOs operating in 127-142 GHz frequency range. This frequency range is used because the 10 μm wide and 1 μm long bridge requires a large central part of spiral antenna, while the size of that central part limits the high frequency response of the antenna. The curves of output power versus IF for the devices operating at transition temperatures T_c are presented on Fig 4. The experimental data are marked as triangles for the 10 nm thick device, squares for the 4.2 nm one, and circles for the 3.5 nm one, and are best fitted by the cut-off frequency of 100 MHz, 300 MHz, and 400 MHz, respectively.

In order to measure the gain bandwidth at physical temperatures well below T_c and to provide uniform electron temperature distribution, it is necessary to apply a high enough magnetic field and to keep DC and LO powers low. The magnetic field lowers the device T_c, and the operating point can be achieved at a low physical temperature and low bias current and LO power. The superconducting solenoid provides a magnetic field of up to 4 T perpendicular to the device surface. This field is enough to perform measurements at temperatures approximately 2 K lower than the transition temperature of the device. No change in the gain bandwidth is observed in this temperature range.

The diffusivity of the superconducting film can be derived from the dependence of critical magnetic field H_{c2} on temperature according to [6]:

$$D = 1.086[(-dH_{c2}/dT)_{T=Tc}]^{-1}$$

The dependence of the critical magnetic field H_{c2} on temperature is measured using the same superconducting solenoid providing a 4 T magnetic field. The obtained H_{c2} versus T for 4 nm thick NbTiN film deposited on Si substrate with an

MgO buffer layer is presented on Fig. 5. The corresponding value of the diffusivity is $D = 1.13$ cm^2/s.

Discussion

For a device operating at $T=T_c$, when the distribution of effective electron temperature is uniform along the bridge, the hot electron bolometer's time constant τ_{ph} depends only on τ_{eph} and τ_{esc}. The gain bandwidth of phonon-cooled device depends on temperature via electron-phonon interaction time and on film thickness via phonon escape time. As can be seen from Fig. 6, the IF bandwidth of the studied 1 μm long NbTiN mixers is inversely proportional to the thickness of the superconducting film. Taking into account that gain bandwidth does not noticeably change with temperature, we can assume that τ_{eph} in the case of 3.5 nm or thicker NbTiN films deposited on MgO layer over Si substrate is much shorter than τ_{esc} and does not influence the gain bandwidth. The gain bandwidth of those devices is limited only by the escape of non-equilibrium phonons to the substrate, and the bolometer time constant is equal to τ_{esc}, which depends on film thickness as follows [3]:

$$\tau_{esc} = 4d/\alpha u,$$

where α is the acoustic mismatch between the superconducting film and the MgO layer, u is the speed of sound in NbTiN.

The gain bandwidth obtained at low physical temperatures under optimal pumping by LO power depends on bias voltage due to electro-thermal feedback. The influence of this effect decreases with the increase of bias voltage. Hence, the results obtained at a larger bias (operating point 2) should be closer to the results obtained under uniform distribution conditions than those obtained at the optimal operating point.

The increase in gain bandwidth of the devices based on 3.5 nm thick NbTiN film from 0.4 GHz to 1.5 GHz with the change of the bridge length from 1 μm to 0.13 μm can be explained if the diffusion cooling mechanism is considered. The bolometer's time constant τ_Θ approximately depends on phonon relaxation time and on diffusion relaxation time as follows:

$$1/\tau_\Theta = 1/\tau_{ph} + 1/\tau_{diff},$$

where τ_{ph} is the bolometer's time constant neglecting diffusion cooling and τ_{diff} is the time constant of the bolometer as if the phonon cooling did not take place. The analysis of diffusion cooling predicts the following dependence on the bridge length L for τ_{diff} [4]:

$$\tau_{diff} = \pi^2 L^2/D,$$

where D is an electron diffusion constant in the superconducting material of the HEB mixer. The gain bandwidth of a device with fixed film thickness depends on the bridge length according to the following equation:

$$f_{cut\text{-}off} = (\pi^2 \tau_{ph} D + L^2)/2\pi\tau_{ph} L^2.$$

This dependence is represented in Fig. 7 along with our experimental data for the gain bandwidth. The theoretical predictions do not fit the experimental data completely, and for shorter bridge lengths the cut-off frequency is much lower than it is provided by the experimentally obtained diffusivity. This effect was not systematically studied, and we can only make a guess that it is due to a finite area under contact pads, in which electrons out-diffuse from the superconducting film into cold metal pads.

The noise temperature of the heterodyne receiver operating at the 2.5 THz LO frequency employing NbTiN mixer is higher than that reported in [7] for NbN HEB mixer. This result is not yet conclusive, because the normal state resistance of the superconducting bridge is less than 20 Ohm and causes noticeable mismatches with both RF circuit (antenna impedance is approximately 75 Ω) and IF chain (isolator input impedance is 50 Ω). We believe that a device with appropriate normal state resistance will be able to demonstrate improved noise performance.

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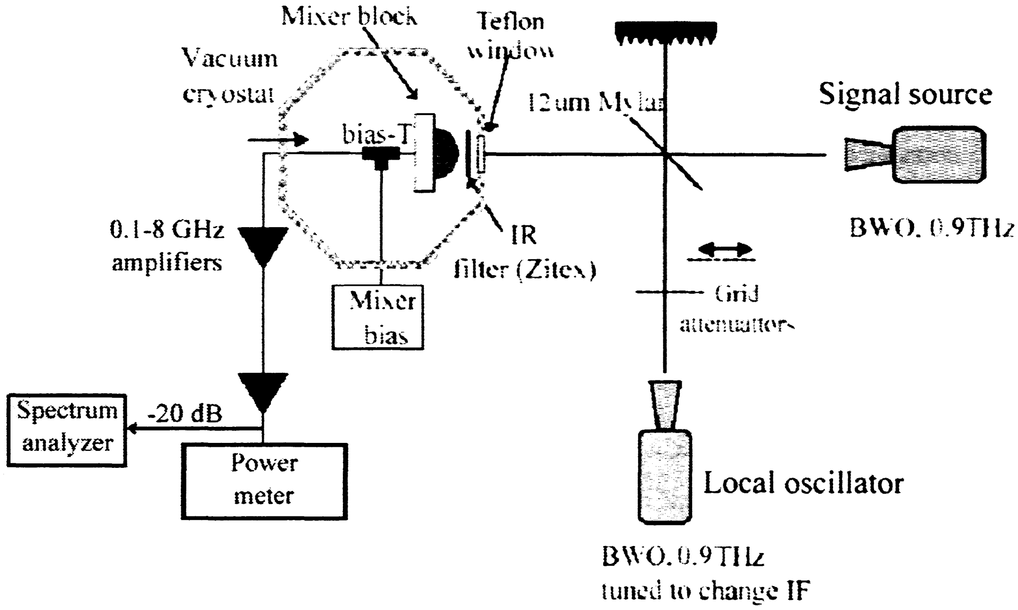

Fig. 1 Experimental setup for heterodyne measurements at 0.9 THz frequency

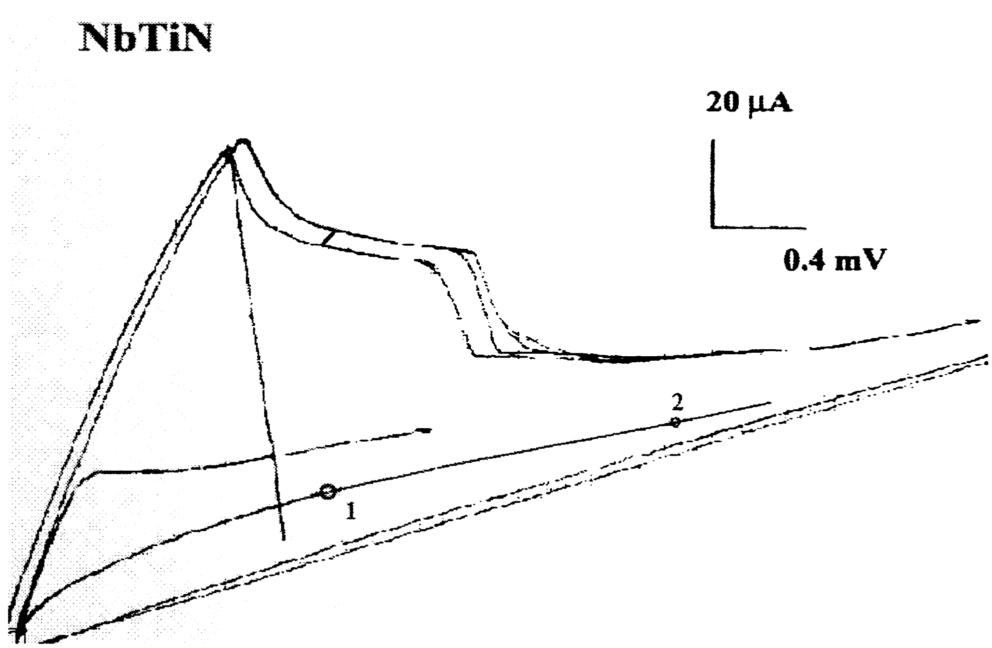

Fig. 2 Family of IV-curves for different pumping RF power

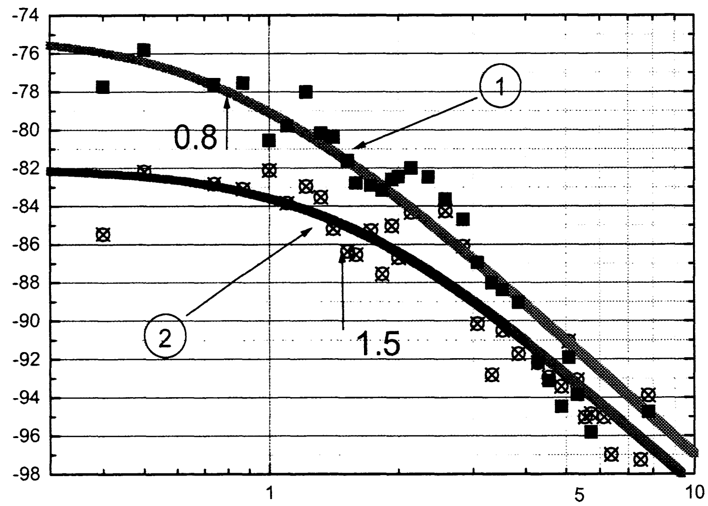

Fig. 3 Output power as a function of IF for 0.13 μm long device based on 3.5 nm thick film. Experimental data are marked by squares (for optimal operating point) and crossed circles (for larger bias voltage).

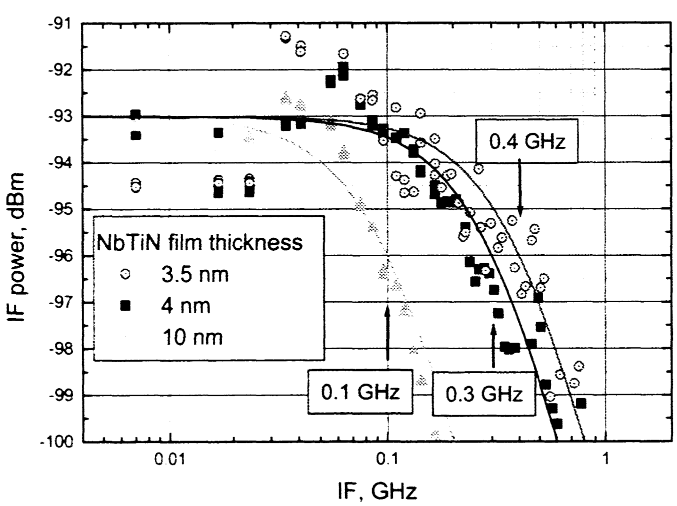

Fig. 4 Output power as a function of IF for 1 μm long devices with different NbTiN film thickness

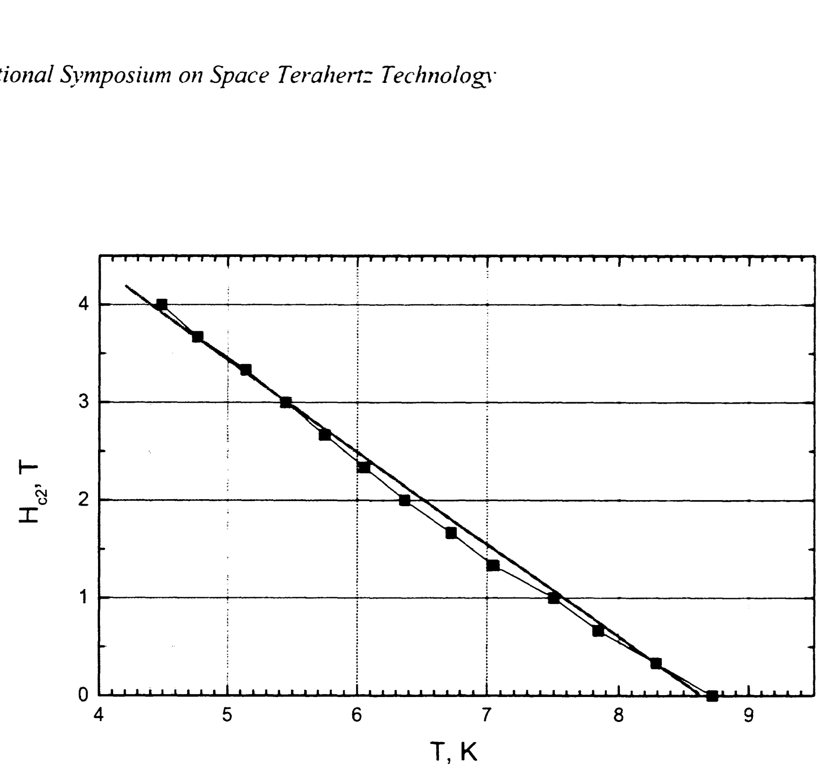

Fig. 5 Critical magnetic field as a function of temperature for 4 nm thick NbTiN film deposited on MgO layer over Si substrate

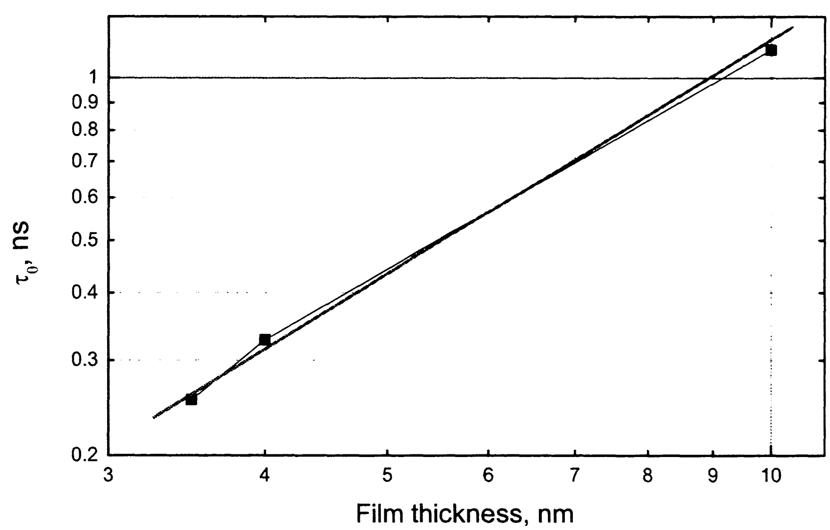

Fig. 6 The cut-off frequency as a function of film thickness

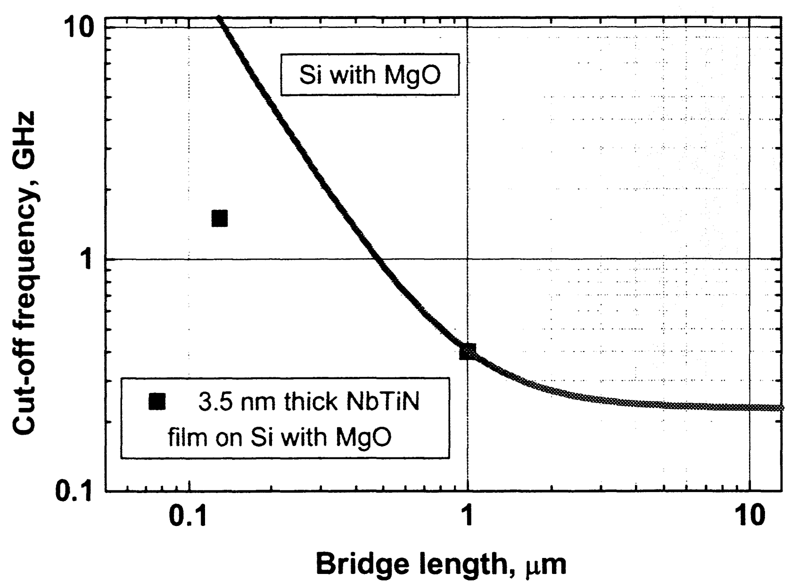

Fig. 7 The cut-off frequency as a function of bridge length