Experimental Study of NbTiN Microstrip Lines

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Abstract—**Amorphous NbTiN is widely applied in superconducting electronic device due to the merits of wide energy gap, high Tc and mitigated requirement in fabrication. Its highly disordered feature also makes it a candidate material for parametric amplification. It is found that the resistivity and film stress of NbTiN film strongly depend on fabrication conditions. To build up the correspondence between the fabrication conditions and the desirable electrical performance, we designed, fabricated and measured NbTiN microstrip resonators. The principal result is that the unloaded Q factor of the resonators does not depend on the film normal state resistivity. This result is consistent with the dirty superconductor theories given by Pippard, Ginsberg-Landau, and Mattis-Bardeen. Our study also provides an accurate method to determine the gap energy of NbTiN.**

I. Introduction

Niobium Titanium Nitride (NbTiN) is a wide-gap superconductor that shows good electronic performance in amorphous texture. Without the requirement of epitaxy, micro-fabrication labs can conveniently fabricate NbTiN thin film devices on various substrates and at room temperature. Because of its high Tc and wide energy gap, it is especially useful in THz frequencies. The amorphous texture causes very short mean free path of the free electrons, and thus results in relatively large resistivity. At superconducting state the dense scattering centers largely reduce the effective coherent length and retard the movement of cooper pair under oscillating electrical field. This effect increases the dynamic inductance of NbTiN. For this reason, NbTiN is a good candidate material for travelling wave superconducting parametric amplifiers.

The superconducting travelling wave parametric amplifiers bring an opportunity of realizing cryogenic microwave amplifiers, which are essential for future large format mm/sub-mm superconducting heterodyne array receivers as well as low noise readout of kinetic inductance detectors (KIDs). They are believed to have lower noise than HEMT amplifiers with reasonable bandwidth (>1GHz). A travelling wave parametric amplifier in form of a CPW has been demonstrated at 0.3K[1]. We are developing parametric amplifiers based on microstrip lines[2]. Compared with CPW devices the microstrip amplifiers can be more compact, broader in bandwidth. The microstrip line has to be low in RF loss to avoid pump tune attenuation, and be large in kinetic inductance to minimize the device size. The figure of merit of the microstrip lines for a parametric amplifier is Q factor, $Q = \beta/2\alpha$, where β is the phase constant and α is the attenuation constant. This transmission line Q factor equals to the Q factor of a resonator consisting of the microstrip line.

There are three groups of evaluation parameters from film deposition to device performance. In electric evaluation, Q is measured. In thin film analysis, the parameters are Tc, resistivity, stress and thickness, which are determined by the third group, fabrication conditions, such as Ar pressure, Nitrogen flow rate and sputtering power. The relationship between these three groups of parameters is not apparent. From our experimental results, we found that Ar pressure strongly influences the film resistivity and stress but not Tc. It is not difficult to change the film resistivity within a range of a factor of two or three by adjusting Ar pressure. By measuring the Q factor of these samples, we found that the Q factor is independent of the film normal state resistivity. This intuitively unexpected result is actually a result of reduction of superconducting order parameters by introducing defects in the film, which were discovered by Pippard[3] and accurately formulated by Mattis and Bardeen[4].

II. Device Design and Film Deposition

A. Device Design

The test sample contains six open-ended microstrip resonators with one end capacitively coupled to readout CWP centre strip. Fig. 1 shows the configuration and a circuit diagram. The microstrip line consists of NbTiN/SiO_2/NbTiN tri-layer with nominal thickness of 50 nm for all three layers. The strip width is 2μm corresponding to about 50 Ohm characteristic impedance. To achieve the sample characteristic impedance, the width of center strip and gap of CWP readout line are designed to be 50μm and 2μm respectively. We employed an inversed microstrip layout, in which the conducting strip is deposited prior to the ground plane, in order to allow a good film quality of the narrow strip and avoid step coverage problem in the ordinary configuration.

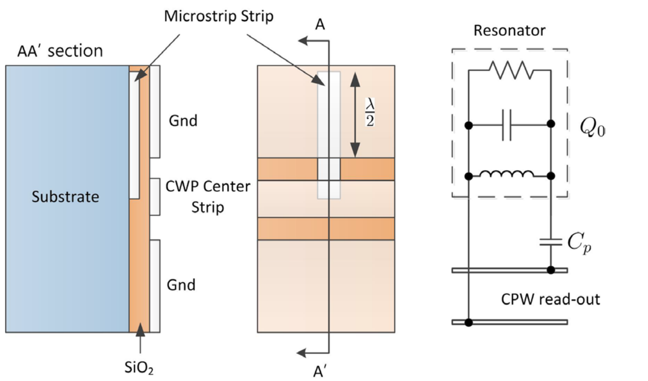

Fig. 1 The layout configuration (not in scale) and the circuit diagram of the test sample.

The resonators on the sample are shifted in resonance frequency. The coupling capacitances of each resonator are set to be different in order to improve accuracy in Q measurement at different temperatures, with which the unloaded Q (referred to as Q_0) varies considerably.

B. Film Deposition

NbTiN films are deposited with a DC magnetron. The target is NbTi with a weight ratio of Nb:Ti=4:1. The reactive gas N_2 is introduced together with Ar. We have previously found that once the N_2/Ar flow ratio surpasses 15%, the T_c will not change by further increasing N_2 ratio. In the following study, we fixed the N_2/Ar flow ratio to 20% and adjusted the throttle valve to control the overall pressure. The dependences of film resistivity and stress on the sputtering pressure are plotted in Fig. 2 and 3.

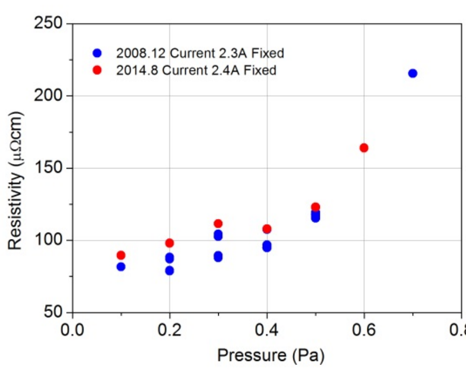

Fig. 2 The dependence of film resistivity on sputtering pressure.

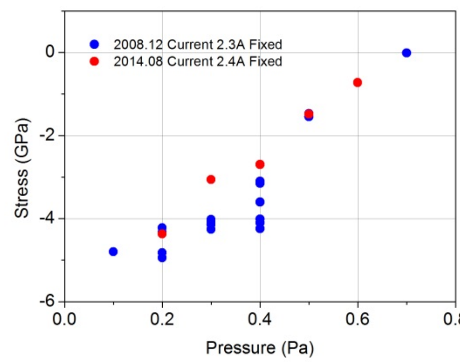

Fig. 3 The dependence of film stress on sputtering pressure.

We observed that the resistivity increases with increasing pressure, with a tendency of saturation at low pressure end, and that the film stress shows a roughly linear dependence on the pressure. The two phenomena are believed to be caused by neutral Ar atom peening on the film[5]. A small part of Ar atoms are ionized in plasma. Once an Ar^+ ion diffuses into the cathode sheath, it is accelerated by the electron field and bombards the target to release Nb and Ti. However some of Ar^+ ions encounter elastic collisions, neutralized by recombining an electron at the target surface and reflected. The reflected neutral Ar atom will not de-accelerated by the sheath filed and head for the substrate. The bombardment of these high energy Ar atoms on the film causses compressive stress and condenses film texture, and thus lead to reduction in resistivity. If the pressure is so high that the mean free path of these atoms is shorter than the target-substrate distance, their energy will be attenuated by collisions. In other word they are thermalized. For a typical target-substrate distance of 10 cm, as the case of our sputtering system, the characteristic pressure for thermalization is about 0.1Pa. Since the sputtering pressure that we adopt is close to this value, the strong correlation between the sputtering pressure and the film quality arises, especially in terms of resistivity and stress.

III. Resonator measurement

The microstrip resonators are measured with a network analyser in a mechanical cryogenic dewar in an ambient temperature ranging from 3.6K to 8K. Several samples are measured in a lower temperature. The S_{21} curves are recorded as a function of the ambient temperature, which is adjusted by a heater fixed on the cold plate. A typical group of resonance curves is shown in Fig. 4.

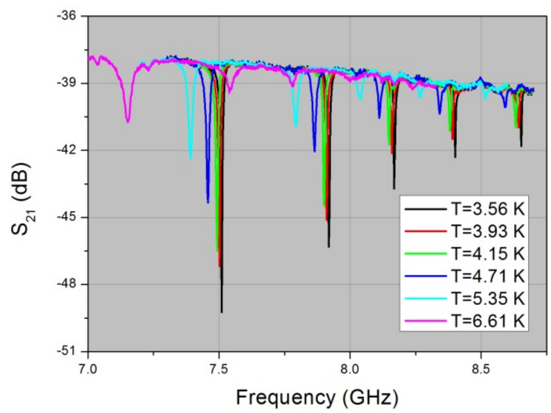

Fig. 4 Resonance curves of a test sample at various temperatures.

The overall Q_t factor and the coupling factor, Q_c, can be obtained by a curve fitting process. The fitted Q_c factor is reasonably consistent with the value calculated from the coupling capacitance. From Q_t and Q_c, the unloaded Q_0 is derived. The final Q_0 is an average of all six resonators.

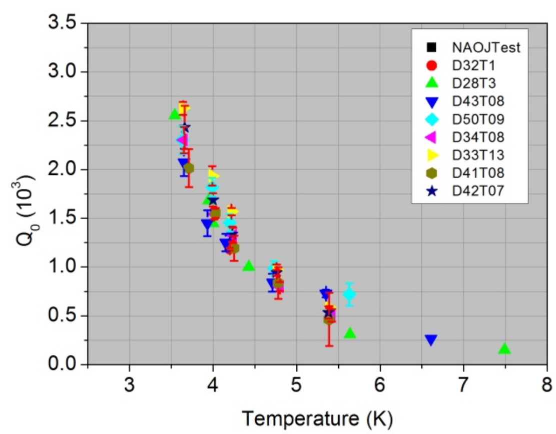

Fig. 5 The dependence of Q_0 on ambient temperature of samples. These samples have different resistivity but show similar Q_0.

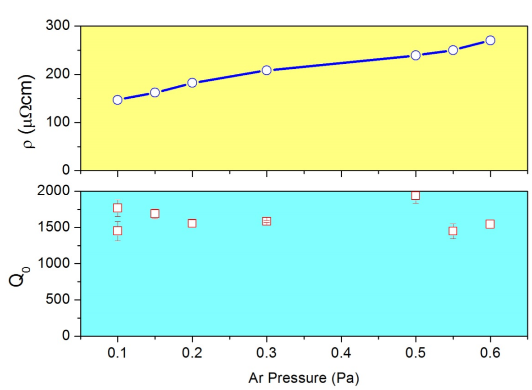

Fig. 6 The Q_0 measured at 4K and the resistivity of NbTiN as a function of sputtering pressure.

The dependence of Q_0 on temperature of all the measured samples is plotted in Fig. 5. The NbTiN films of those samples are deposited at different sputtering pressure and thus are different in resistivity. However, little difference in Q_0 can be observed. Fig. 6 illustrates this phenomenon more clearly. By adjusting the Ar pressure from 0.1 Pa to 0.6 Pa, the resistivity can be doubled. But although some random scattering exists, there is no clear difference between these samples in Q factor. This suggests that although the attenuation factor α increases with increasing resistivity, the propagation constant β increases accordingly to make $Q=\beta/2\alpha$ unchanged. This behaviour can be explained by Pippard and Mattis-Bardeen theory, which involves the effect of mean free path of the free electrons.

IV. Discussion

The role of mean free path in a superconductor was revealed by Pippard when he was aware of that the rigid superconducting electron density in London theory is not correct[3]. He empirically introduced an effective coherent length, ξ, which is the harmonic average of the mean free path, l, and the intrinsic coherent length, ξ_0. His treatment equivalently means that the superconducting electron density is reduced by ξ/ξ_0. Since the superconducting electron density is reduced, the superconducting electrons have to move faster to keep the same current, and thus have more kinetic energy. This induces larger kinetic inductance of the transmission line composed with NbTiN with shorter mean free path, or in other words, normal state resistivity. Mattis and Bardeen treated this issue through a microscopic approach[4], and therefore it inherently includes the effect of mean free path, temperature and frequency. The effect of mean free path can be seen from the imaginary part of the conductivity given by Mattis and Bardeen, which is proportional to the normal state conductivity. The Q factor can be calculated by $Q=\sigma_2/\eta\sigma_1$, where η is the kinetic inductance ratio of transmission line. It is close to 1 in microstrip line case. If $\hbar\omega \ll \Delta$ and $kT \ll \Delta$, to which our measurement condition meets, the Q factor can be simplified as

$$Q=-\frac{\pi}{4}\frac{1}{\xi\ln\xi}e^{\frac{\Delta}{kT}} \qquad (1)$$

where $\xi=\hbar\omega/2kT$. Because the normal state conductivity σ_n appears both in the real and imaginary part of the Mattis-Bardeen complex conductivity expressions, the Q value becomes independent of σ_n. This is the conclusion observed from Fig. 5 and Fig. 6.

The Mattis-Bardeen expressions are not only useful in qualitatively understanding the experimental results but also quantitative instructive. (1) can be written as

$$\ln Q+\ln\xi+\ln(-\ln\xi)=\ln\frac{\pi}{4}+\frac{\Delta}{kT} \qquad (2)$$

The energy gap is the slope of straight line given by $x=1/kT$ and $y=\ln Q+\ln\xi+\ln(-\ln\xi)$. Fig. 5 is re-plotted as Fig. 7 by this method and the energy gap is extracted to be 1.95 ± 0.07 meV.

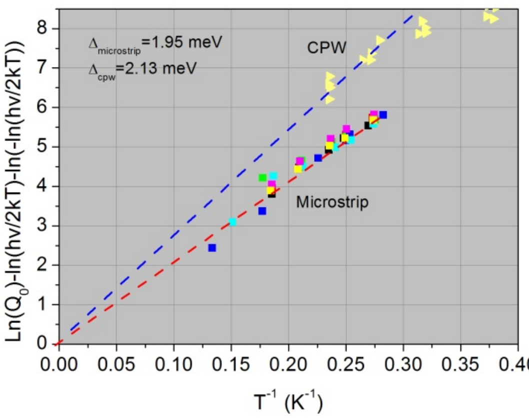

Fig. 7. Extraction of energy gap according to Mattis-Bardeen theory

In Fig. 7 we also show results of CPW NbTiN resonators, which shows an order of one magnitude higher Q factor at 4K. The reasons are two folds. One is that the energy gap of NbTiN in CPW, 2.13 meV, is slightly higher, and the other is that the kinetic inductance ratio for the CPW is half of that for the microstrip lines. An smaller ratio leads to larger Q.

I. CONCLUSIONS

Our experimental results show that sputtering pressure considerably influences the mean free path of the NbTiN film, while not changing the Tc and the energy gap, and that the Q factor of NbTiN microstrip resonators is independent of the normal state resistivity of the film. This independence can be explained by Mattis-Bardeen theory. Base on that, the energy gap can also be determined. These results help in building up relations between fabrication and devices electronic performance. The NbTiN microstrip line will be optimized for development of travelling wave parametric amplifiers.

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