Extended Abstracts of the 2018 International Conference on Solid State Devices and Materials, Tokyo, 2018, pp1221-1222

Penetration depths of superconducting TiN films estimated from coplanar waveguide resonators

Wei Qiu*, Hirotaka Terai

Frontier Research Laboratory, Advanced ICT Research Institute, National Institute of Information and Communications Technology (NICT)
588-2, Iwaoka, Nishi-ku
Kobe 651-2492, Japan
Phone: +81-78-969-2171 E-mail: qiuwei@nict.go.jp

Abstract

Precise design and fabrication of superconducting quantum qubit are both essential requirements for physical implementation of quantum computing and/or quantum information processing. Nitride superconductors are vigorously studied as low loss materials to realize microwave resonators with high quality factors. However, large London penetration depth λ_L of nitride superconductor with polycrystalline structure sometimes causes large kinetic inductance, giving rise to the large frequency shift of the resonant frequency of coplanar waveguide (CPW) resonator. In this research report, we evaluate the kinetic inductance of TiN films from the resonance shifts of the CPW resonators. The estimated penetration depths of the TiN films were 680, 1060 and 1290 nm for the TiN films prepared at an ambient temperature and the total gas pressures of 4, 6 and 8 mTorr, respectively, which agree well with penetration depths of 660, 1070 and 1250 nm calculated from the relationship among λ_L, resistivity ρ and critical temperature T_C in the weak-coupled BCS limit. In comparison, CPW resonator made of (200) oriented TiN film prepared at 800°C shows much smaller shift in resonant frequency due to its smaller penetration depth than that of polycrystalline TiN. The estimated λ_L was 80 nm, which is also consistent with the λ_L estimated from the measured ρ of 3.7 μΩ cm and T_C of 5.4 K in the weak-coupled BCS limit.

1. Introduction

Nitride superconducting materials have drawn dramatic interests to study the loss mechanics behind short coherence time in superconducting qubit. Many reported research have shown the improvement of loss by developing high Q_i microwave resonators using superconducting TiN material [1-5]. However, to achieve high Q_i over 10^6 near single microwave photon power $\langle n_{photon} \sim 1 \rangle$ remains extremely challenge [4]. Meanwhile in superconducting microwave resonator device, the resonance frequency can dramatically shift to lower frequency due to the larger than expected kinetic inductance contribution to the total inductance in resonator. One needs to consider the impact of such large kinetic inductance in future qubit circuit design. Surprisingly, only few research have shown related study so far [3]. In this reported study, superconducting microwave resonators have been developed by using TiN material deposited at various condition. Their kinetic inductance, thus the penetration depths have been also evaluated by measuring the frequency shifts of their resonance.

2. Device Fabrication and Measurement

Coplanar waveguide resonators have been fabricated by using superconducting TiN on single crystal Si substrate. Prior to the TiN film deposition by dc-magnetron sputtering, all substrates have been treated by a mixed solution of sulfuric acid (H_2SO_4) and hydrogen peroxide (H_2O_2), followed with a diluted hydrofluoric acid (HF) solution to remove the native oxide and form a hydrogen termination on Si surface. TiN films deposited at room temperature at different total gas pressure of 4, 6, and 8 mTorr while maintaining the ratio of Ar/N_2 gas flow. For (200)-oriented TiN film, the substrate is heated at 800°C during the deposition at pressure of 1 mTorr. X-ray diffraction analysis show the sharp peak at 42.66°, corresponding to a lattice constant of 0.423 Å for high temperature sputtering TiN film, while TiN films deposited at room temperature all have polycrystalline structures.

The superconducting transition temperatures T_c are 4.7 K, 4.3 K, and 4.7 K for TiN films deposited at 4 mTorr, 6 mTorr, and 8 mTorr at room temperature, respectively. The resistivity ρ_{10K} are 222 μΩ cm, 532 μΩ cm, and 786 μΩ cm at three pressure sputtering conditions. For (200)-oriented TiN film deposited at high substrate temperature, T_c and ρ_{10K} are 5.4 K and 3.7 μΩ cm.

To examine rf properties, TiN films have been patterned into half-wavelength $(\lambda/2)$ coplanar waveguide resonator (CPWR) by our standard photolithography process before reactive ion etch (RIE) by CF_4 plasma (Figure 1). The width of the central conductor is W=20 μm and gap distance between center conductor and the ground planes is S=11.9 μm to keep the impedance of transmission line Z_0=50 Ω. The lengths of CPWRs are chosen to have a nominal resonance around 9.3 GHz, modeled by finite element simulation for high frequency circuit [6].

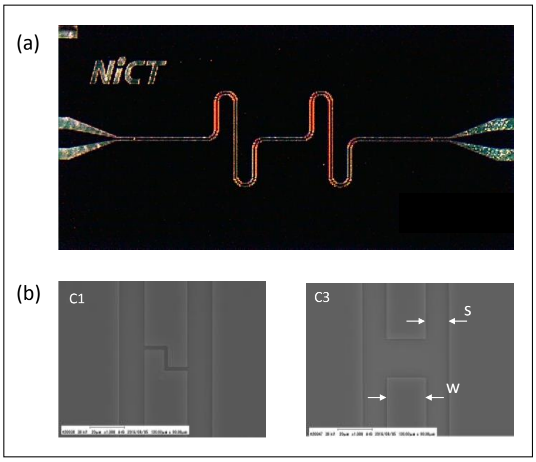

Fig. 1 CPWR designs. (a) An overall view of a full-size (5mm × 2.5mm) CPWR device. (b) Zoom-in SEM images of two resonators C1 and C3 with the same center conductor linewidth W=20 μm and the same gap distance between center conductor and ground planes S=11.9 μm, but differed by different interdigital coupling capacitance.

All resonator devices were measured at the temperature below 20 mK in an Oxford Instrument Triton400 dilution refrigerator system. Microwave signal with frequencies near the resonance generated from the output port of a vector network analyzer passing a series of attenuation placed at room temperature (from 30 dB to 92 dB) and inside the refrigerator (total of 50 dB) before reaching at the device package. The output of signal was amplified by a cryogenic amplifier with a bandwidth of 4-12 GHz and gain of 35 dB located at 4.2 K. The output signal was further amplified by 65 dB low-noise amplifier located at room temperature before being picked up by the input port of the network analyzer. From the S-parameters measurement, Q_i was determined at different input microwave power for each resonator chip (Figure 2). The highest Q_i of 1.02×10^6 has been achieved using TiN film developed in a high total pressure environment at room temperature.

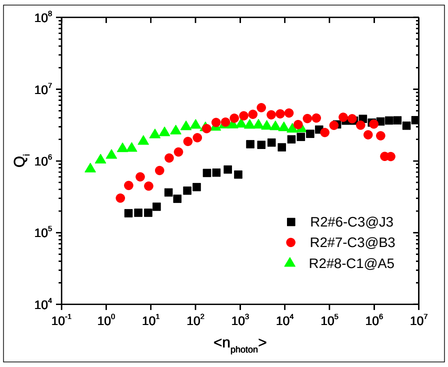

Fig. 2 Quality factor as a function of microwave photon number measured at 20 mK for three CPWRs developed by using TiN films under different total pressure. The highest Q_i value of 1.02×10^6 has been achieved in TiN film deposited at 8 mTorr and the lowest Q_i value of 1.85×10^5 with TiN film deposited at 4 mTorr.

For TiN-CPWRs developed at room temperature, the shift of the resonance increases as the total pressure increases from 4 mTorr to 8 mTorr. The shifts of the resonance are so large that the fundamental modes of resonators developed under high total pressure condition are either towards the lower limit or out of the amplifier's bandwidth. Only 2nd harmonic or 3rd harmonic can be overserved within the bandwidth of the amplifier as indicated in upper-scripted (Table I). We conclude that such resonance shifts are due to significant kinetic inductance contribution to the overall inductance. In comparison, we found that the shift of resonance is much smaller in CPWR using (200)-oriented TiN film developed at high substrate temperature, indicating only a small portion of kinetic contribution in such device and much shorter penetration depth for (200)-oriented TiN film. By measuring the resonance shifts for each resonator, we calculate the kinetic inductance and London penetration depth, λ_L by the similar method described in [3, 7]. These results agree well with the theoretical estimation by using a weak-coupled BCS model developed in [8]. The results of λ_L are listed in Table I.

Table I Measurement Results

ID	Pres. (mTorr)	T_c (K)	ρ_{10K} (μΩ cm)	f_{design} (GHz)	f_m (GHz)	λ_L (nm)	Q_i ($\times 10^5$)
R1#4-C1	8	5.4	3.7	9.304	9.219	80	0.11
R2#6-C3	4	4.7	222	9.304	6.037	680	1.85
R2#7-C3	6	4.3	532	9.304	4.383(2)	1060	3.02
R2#8-C1	8	4.7	786	9.299	3.410(3)	1290	10.2

3. Conclusions

We studied the losses in CPWRs by using superconducting TiN materials deposited under different total pressures at room temperature and (200)-oriented TiN film deposited at high substrate temperature. Internal quality factor Q_i of over 10^6 has been achieved in TiN-CPWR developed at 8 mTorr. We found larger than expected kinetic inductance contribution are responsible for the observed shifts in resonant frequency in TiN-CPWRs developed at room temperature. More importantly, London penetration depth λ_L calculated from the resonance shifts show good agreement with the theoretical estimation using BCS model.

Acknowledgements

This work is under supported by JST ERATO (Grant no. JPMJER1601) and CREST (Grand no. JPMJCR1775).

References

[1] B. A. Mazin *et al.*, Appl. Phys. Lett., **96** (2010) 102504
[2] H. G. Leduc *et al.*, Appl. Phys. Lett. **97** (2010) 102509
[3] M. R. Vissers *et al.*, Appl. Phys. Lett. **97** (2010) 232509
[4] J. M. Sage *et al.*, J. Appl. Phys. **109**, (2011) 063915
[5] W. Qiu *et al.*, IEEE Trans. Appl. Super. Vol. 27, No. 4 (2017)
[6] Ansys HFSS®
[7] W. H. Chang, J. Appl. Phys. 50, 8129 (1979)
[8] T. P. Orlando *et al.*, Phys. Rev. B 19, 4545 (1979)