

Characterization of Superconducting NbN, WSi and MoSi Ultra-Thin Films in Magnetic Field

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Abstract—The system detection efficiency of superconducting nanowire single-photon detectors (SNSPD) has rapidly improved in recent years. In this study, we fabricated NbN, WSi and MoSi ultra-thin films, which are widely used for SNSPD fabrication, employing magnetron sputtering. We characterized the films in the presence of a magnetic field to study the upper critical magnetic field H_{c2} and the anisotropy. According to the results obtained in our experiments, we calculated the coherence length and diffusion coefficient of these films. The knowledge of these parameters will guide the modelling and the interpretation of the different features observed in SNSPD made out of NbN, WSi and MoSi.

Index Terms—Anisotropy, superconducting single-photon detector, ultra-thin films, upper critical magnetic field.

I. INTRODUCTION

SUPERCONDUCTING nanowire single-photon detector (SNSPD) demonstrates excellent performance in single-photon detection due to its low dark count rates, fast detection speed, high time resolution and high detection efficiency [1]–[4]. The recently developed SNSPD achieved near-unity system efficiency and is widely applied in quantum key distribution [5], optical quantum computing [6], space-ground laser communication [7], etc.

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Different types of superconducting films have been used to make SNSPD devices, among which NbN films are widely used [8]–[11]. By adopting the sandwiched twin-layer nanowire structure that features a very thin insulating layer in between, it reaches the highest System Detection Efficiency (SDE) of NbN SNSPDs which is $\sim 98\%$ at a wavelength of $\lambda = 1590$ nm and a temperature of $T = 0.8$ K [12].

Other SNSPD devices based on WSi [13]–[16] and MoSi [17]–[19], often reported as amorphous films, have lower energy gaps and lower substrate selectivity. The SDE record of WSi SNSPD is $\sim 93\%$ at $\lambda = 1550$ nm and $T = 0.12$ K [13]. Furthermore, because of the lower energy gap, WSi SNSPD can also work in mid-infrared band. MoSi SNSPD also achieved 98% SDE at 1550 nm [19].

A great number of experiments has shown that detection efficiency (DE) of SNSPD drops fast at wavelengths larger than a critical value called cut-off wavelength λ_c [20]–[22]. The cut-off wavelength is important for studying SNSPD that work in the mid-infrared. Hot belt and hot spot models are used to calculate the cut-off wavelength [23]. To figure out which model to use in the experiment, one needs to conduct quantitative assessments, namely measure and calculate many material parameters. As it is known the photon count rate changes in the presence of a magnetic field. Therefore, studies of the properties of thin films as a function of the magnetic field intensity and the angle of the field with respect to the normal to the film surface are expected to increase our understanding of the detection mechanism leading to further improvements of the device performance.

In this paper, we prepared three types of superconducting ultra-thin films by magnetron sputtering at room temperature. To measure film parameters, we applied various magnetic fields and calculated the coherence length and diffusion coefficient. We also studied the anisotropy parameters of these ultra-thin films and found the anisotropy parameter of NbN are larger than those of other amorphous films.

II. EXPERIMENTS AND RESULTS

A. Thin-Film Growth

The deposition methods of WSi and NbN are similar to those applied in the previous works [24]–[25].

MoSi thin films were deposited on a thermal silicon oxide substrate using magnetron co-sputtering in high vacuum (base pressure $< 1 \times 10^{-5}$ Pa). The purity of the Mo target and the Si

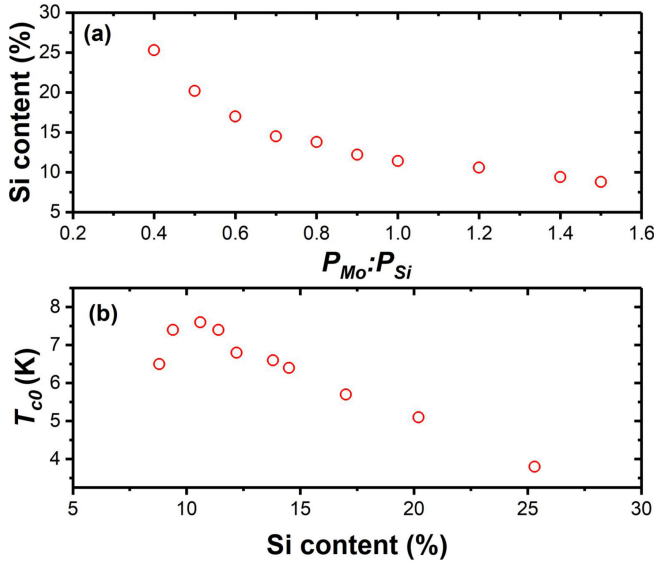


Fig. 1. (a) Si content of MoSi films prepared with different sputtering power ratios. (b) The zero-resistance critical temperatures (T_{c0}) of MoSi films versus Si content.

target is 99.99%. Both targets had a diameter of 2 inches. The Mo target was sputtered by direct-current (DC) power supply in constant power mode, whereas the Si target was sputtered using a radio-frequency (RF) power supply. Initially, we introduced 21 sccm of argon in the process chamber, keeping the pressure at 0.8 Pa. The substrate holder rotates during sputtering with a speed of 50 round/min, and is maintained at room temperature by a water-cooling system. After depositing a MoSi film, we sputtered a ~ 3 nm Si layer in situ to prevent oxidation.

In our study, we fixed the RF power at 100 W, and then changed the DC power to tune MoSi film composition. The chemical composition was identified by an Auger electron energy spectrometer (AES) after deposition immediately. Fig. 1(a) shows that the Si content in the MoSi films decreases with increasing the sputtering power ratio P_{Mo}/P_{Si} , here P_{Mo} and P_{Si} represent the sputtering power of Mo and Si respectively. Fig. 1(b) demonstrates the zero-resistance critical temperatures (T_{c0}) of the MoSi films with approximately 100 nm thickness vs. the Si content. When the Si content is between 9%~12%, the T_{c0} of the MoSi film is above 7 K. However, increasing and decreasing Si content leads to a decrease in T_{c0} . Both figures show the optimal film composition: the sputtering power $P_{Mo} = 120$ W, $P_{Si} = 100$ W, with 10.6% Si content and 7.6 K T_{c0} of the film. The deposition rate on the thermal silicon oxide substrate was 0.38 nm/s.

B. Measurement and Results

We deposited 5 nm NbN on MgO substrate, 5 nm MoSi and 6 nm WSi on thermal silicon oxide substrate. The reason NbN is grown on a MgO substrate is achieve a better lattice structure. Fig. 2 shows the temperature dependence of the film resistance under no magnetic field. The T_{c0} of the films are shown in Table I.

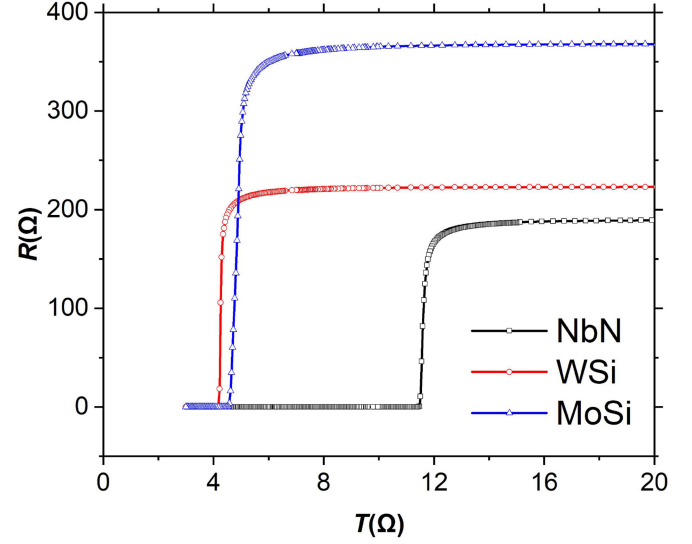


Fig. 2. Temperature dependence of resistance without magnetic field.

TABLE I
THE PARAMETERS OF THREE THIN FILMS

Materials	Thickness (nm)	T_{c0} (K)	$H_{c2\perp}(0)$ (kOe) / n	$H_{c2\parallel}(0)$ (kOe) / n	$\xi_{GL}(0)$ (nm)	$\xi_{GL}(T)$ ^a (nm)	D (cm ² /s)
NbN	~ 5	11.63	424.3 / 0.47	150.4 / 1.10	4.7	30.9	0.77
WSi	~ 6	4.26	251.1 / 0.52	62.6 / 0.86	7.2	37.2	0.68
MoSi	~ 5	4.86	393.1 / 0.64	102.7 / 1.01	5.7	13.5	0.47

^a ξ_{GL}/T represents the coherence length of the films at the temperature during the measurements.

To investigate the anisotropic properties of the films, we have measured the angular dependence of the ultra-thin films resistance at a temperature slightly below T_{c0} , for several applied magnetic fields up to 90 kOe, respectively, as shown in Fig. 3. Here θ is the angle between the applied magnetic field and the normal direction of the film surface. The configuration of the applied field is shown in Fig. 3(d). An inspection of Fig. 3 shows that the resistance varies significantly with the angle and it has the maximum value at 0° and 180° . This behavior is similar to the result observed in three-dimensional anisotropic YBCO samples [26] or in two-dimensional samples [27]. It may be caused by film anisotropy or two-dimensional effect.

To provide detailed information about films, we calculated the anisotropic parameters γ according to the G-L theory as $\gamma = H_{c2\perp}/H_{c2\parallel}$. Here $H_{c2\perp}$ represents the upper critical magnetic field perpendicular to the film surface, while $H_{c2\parallel}$ represents the upper critical magnetic field parallel to the film surface. To get the $H_{c2\perp}$ and $H_{c2\parallel}$ values, we have measured the temperature dependence of the resistance at various applied magnetic fields for two configurations: (i) $\theta = 0^\circ$; (ii) $\theta = 90^\circ$ as shown in Fig. 4. Fig. 4(a), (c), (e) demonstrate the cases when the magnetic fields are perpendicular to the NbN, WSi, MoSi film surfaces, respectively. Fig. 4(b), (d), (f) are in parallel situations. In Fig. 4,

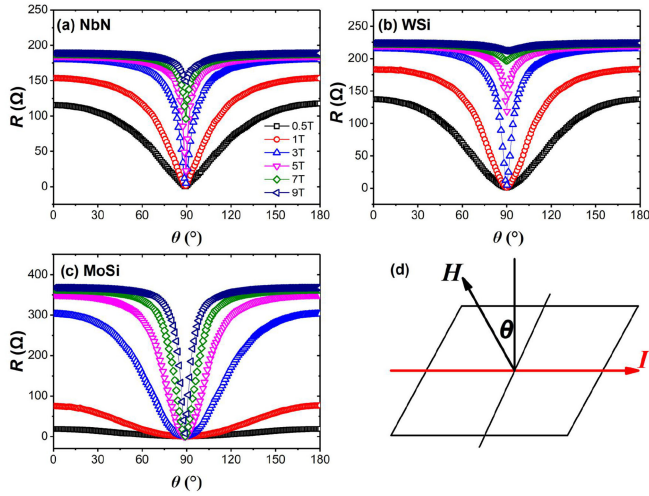


Fig. 3. Angular dependence of the resistance for various fields. (a) NbN film at $T = 11.4$ K, (b) WSi film at $T = 4.1$ K (c) MoSi film at $T = 4.1$ K (d) The configuration of the applied magnetic field.

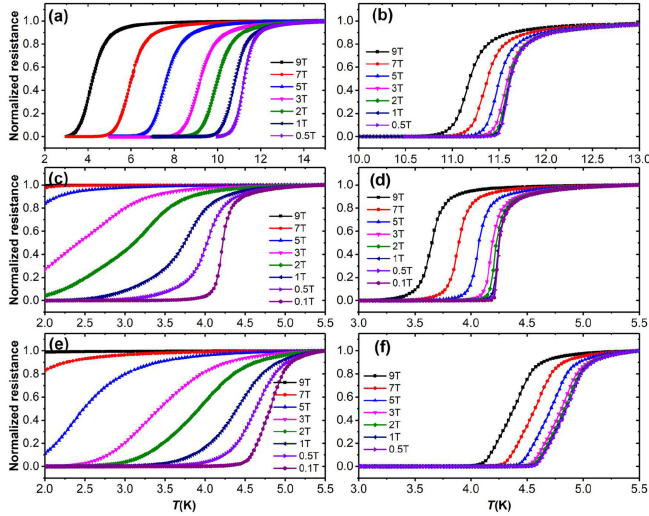


Fig. 4. Temperature dependence of resistance at several different fields. (a), (c), (e) $\theta = 0^\circ$; (b), (d), (f) $\theta = 90^\circ$, (a), (b) NbN film; (c), (d) WSi film; and (e), (f) MoSi film.

we see that the superconducting transition temperature shifts to low temperature when the applied field increases, and it is more obvious in $\theta = 0^\circ$.

The upper critical fields as function of temperature were shown in Fig. 5, where the values of the upper critical field were defined at $R/R_n = 0.5$, here R_n is the normal state resistance. We fit the data by the expression $H_c = H_c(0)(1-T/T_c)^n$ reported in [28]. According to the Eq. (19) in [29]: for two-dimensional materials ($d < \xi(T)$), $n \approx 0.5$, and for three-dimensional materials ($d \geq \xi(T)$), $n \approx 1$, here d represents the thickness of the film, and $\xi(T)$ represents the coherence length of the films at the temperature during the measurements, therefore, all of our ultra-thin film show two-dimensional characteristic during the measurements. The upper critical magnetic field, coherence length ξ_{GL} and diffusion coefficient D are shown in Table I. The function of

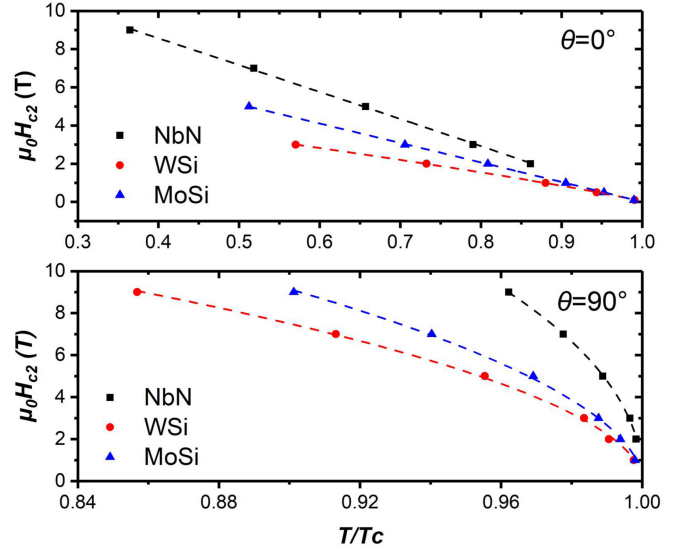


Fig. 5. Temperature dependence of critical field determined by $R = 0.5R_n$. The dash lines are the fitting curves.

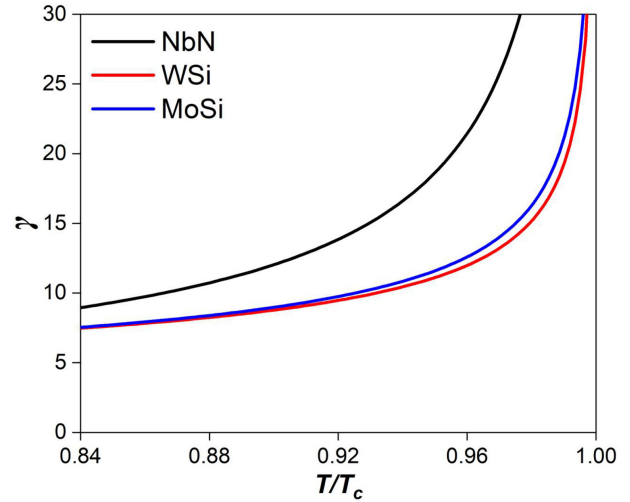


Fig. 6. The function of anisotropic parameters $\gamma = H_{c2//} / H_{c2\perp}$ on T/T_c .

anisotropic parameters $\gamma = H_{c2//} / H_{c2\perp}$ on T/T_c when T is closed to T_c is shown in Fig. 6. $H_{c2//}$ and $H_{c2\perp}$ are determined according to the fitting expression in Fig. 5. The γ of NbN is slightly larger than those of WSi and MoSi.

We also measured electron transport on ultra-thin films for the whole 360° range of in-plane current orientations, as shown in Fig. 7. This allowed us to determine the misalignment between the applied current and the electric field generated by the vortex movement. This reflects the film uniformity and anisotropy. Fig. 7(d) shows the sketch of the cross shaped thin film. The transport measurements were performed using two independent DC currents J_x and J_y , applied at the extremes of the cross legs, allowing to control the orientation (φ) of the total current J_T . The voltage contacts were located in the center of the cross with a separation about $200 \mu\text{m}$ to avoid possible current

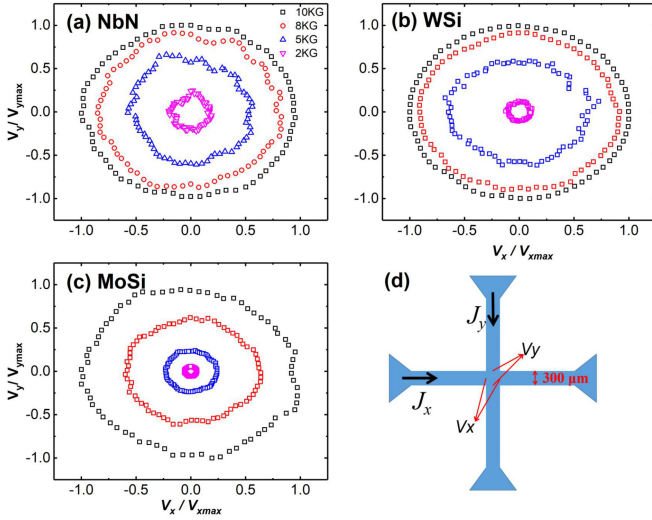


Fig. 7. (a), (b), (c) polar graph $V_x \times V_y$ of NbN, WSi, MoSi thin films for $J_T = 30 \text{ kA/cm}^2$, and (d). sketch of the cross shaped MoSi film. The black arrows represent two independent DC current directions. The red arrow represents the point where the voltage is measured.

inhomogeneities. During the measurement, we swept the angle φ of the total current J_T , while keeping the $J_T = \sqrt{J_x^2 + J_y^2}$ constant. The magnetic field H was applied perpendicular to the film surface.

Fig. 7(a), (b), (c) shows the polar $V_x \times V_y$ for $J_T = 30 \text{ kA/cm}^2$, where the curves have been scaled by dividing by the maximum value for clarity purposes. All curves in different fields are closed to a circle indicate the thin films are an isotropic conductor; an isotropic vortex motion is parallel to the Lorentz force.

III. CONCLUSION

Three types of superconducting ultra-thin films are well deposited by magnetron sputtering at room temperature. We characterized the films at various applied magnetic fields, and calculated their coherence length and diffusion coefficients. We also study the anisotropy parameters of these ultra-thin films and found the anisotropy parameter of NbN is larger than those of amorphous films. The knowledge of these parameters will guide the modelling and increase our understanding of the detection mechanism leading to further improvements of the device performance.

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