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Characterization of low-loss hydrogenated amorphous silicon films for superconducting resonators

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Abstract. Superconducting circuit elements used in millimeter-submillimeter (mm-submm) astronomy would greatly benefit from deposited dielectrics with small dielectric loss and noise. This will enable the use of multilayer circuit elements and thereby increase the efficiency of mm-submm filters and allow for a miniaturization of microwave kinetic inductance detectors (MKIDs). Amorphous dielectrics introduce excess loss and noise compared with their crystalline counterparts, due to two-level system defects of unknown microscopic origin. We deposited hydrogenated amorphous silicon films using plasma-enhanced chemical vapor deposition, at substrate temperatures of 100°C, 250°C, and 350°C. The measured void volume fraction, hydrogen content, microstructure parameter, and bond-angle disorder are negatively correlated with the substrate temperature. All three films have a loss tangent below 10^{-5} for a resonator energy of 10^5 photons, at 120 mK and 4 to 7 GHz. This makes these films promising for MKIDs and on-chip mm-submm filters. © The Authors. Published by SPIE under a Creative Commons Attribution 4.0 International License. Distribution or reproduction of this work in whole or in part requires full attribution of the original publication, including its DOI. [DOI: [10.1117/1.JATIS.8.2.028006](https://doi.org/10.1117/1.JATIS.8.2.028006)]

Keywords: kinetic inductance detectors; filter bank; spectrometer; millimeter-submillimeter; amorphous silicon; dielectric loss.

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1 Introduction

The integrated superconducting spectrometer (ISS)¹⁻³ is a novel astronomical instrument that promises ultra-wideband, high-sensitivity, and three-dimensional imaging spectrometry in the millimeter-submillimeter (mm-submm) band. ISSs enable large arrays of spectroscopic pixels because they are intrinsically scalable due to the compact on-chip filterbank for signal dispersion and because they allow for frequency-domain multiplexed readout of the microwave kinetic inductance detectors (MKIDs).⁴

Currently, the DESHIMA³ ISS has a planar design using coplanar waveguide (CPW) circuit elements. The advantage of this planar design is that it can be fabricated directly on top of a crystalline substrate, in contrast to multilayer circuit elements, which generally make use of a deposited dielectric. Deposited amorphous dielectrics contain two-level system (TLS) defects that introduce dielectric loss and frequency noise.⁵⁻⁷ However, multilayer circuit elements offer various benefits over planar circuit elements. The size of an MKID could be drastically reduced with a multilayer design, and microstrip filters suffer negligible radiation loss compared to planar filters.^{8,9}

The peak transmission $|S_{31}|^2$ through a single isolated mm-submm filter^{10,11} is

$$|S_{31}|^2 = \frac{1}{2} \left(1 - \frac{R}{Q_i} \right)^2, \quad (1)$$

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where $R = F/\Delta F$ is the resolving power and Q_i is the internal quality factor. The $1/Q_i$ is roughly equal to the dielectric loss tangent in the case of a superconducting microstrip filter.^{11–13} An increase in Q_i will enable a proportional increase in R at a particular filter transmission value.

A mm-submm Q_i of 1440 has been achieved with amorphous silicon nitride (SiN_x).¹¹ Recently, Q_i values of 4800 and 8300 were reported for hydrogenated amorphous silicon (a-Si:H)¹² and hydrogenated amorphous silicon carbide (a-SiC:H),¹³ respectively. Further improvement in Q_i is desired to enable filters with higher R .

Although TLSs are successfully modeled by the standard tunneling model (STM),⁵ their microscopic origin remains unknown. The TLSs dominate the dielectric loss in superconducting resonators at microwave frequencies.^{7,12–15} In the STM the TLS density of states is frequency independent, and this leads to the suggestion that a decreased microwave loss translates to increased performance for the mm-submm filters. Currently, the best low-power microwave loss tangents $\tan \delta \sim 10^{-5}$ have been measured for a-Si:H films^{7,12,14,15} and a-SiC:H films.¹³

Due to an observed relation between TLS density and atomic silicon density, it has been proposed that the TLSs in electron-beam evaporated amorphous silicon (a-Si) are related to voids in the material.¹⁶ It was found that a very low void volume fraction can be achieved by depositing at elevated substrate temperatures T_{sub} .¹⁶ Recently, it has been observed that although the TLS-induced internal friction in a-Si correlates with the atomic silicon density, the TLS-induced loss tangent instead correlates with the dangling bond density.¹⁷

In this work, we investigate the effect of T_{sub} on the microstructural and compositional properties of a-Si:H, and we study if these properties relate to the dielectric loss at 4 to 7 GHz and at 120 mK. For this purpose, we deposited a-Si:H films using plasma-enhanced chemical vapor deposition (PECVD) at three different substrate temperatures, and we measured their void volume fraction, hydrogen content, microstructure parameter, bond-angle disorder, and infrared (IR) refractive index.

2 Film Deposition

We deposited the a-Si:H films by PECVD with an Oxford Plasmalab 80 Plus. The substrate temperatures T_{sub} during the PECVD processes were 100°C, 250°C, and 350°C. The T_{sub} was the only parameter that was varied. The deposition parameters are listed in [Appendix A](#). We used crystalline silicon (c-Si) substrates with (100) crystal orientation. Further substrate details and the wafer preparation details depend on the subsequent experiment and are described in the methods of each experiment. For the dielectric loss measurements, we used high resistivity wafers.

3 Characterization at Room Temperature

3.1 Hydrogen Content, Microstructure Parameter, and Infrared Refractive Index

The microstructure of a-Si:H is largely governed by the occurrence of SiH and SiH₂ configurations in the material.^{18–20} The SiH configurations reside mostly in small vacancies, corresponding to up to three missing silicon (Si) atoms¹⁹ per vacancy. This is in contrast to the SiH₂ configurations that exist mostly on the surface of voids with a radius of 1 to 4 nm, corresponding from 10² to 10⁴ missing Si atoms¹⁹ per void. We used Fourier-transform IR (FTIR) spectroscopy in transmission mode to measure the microstructure parameter R^* [Eq. (4)], which quantifies the relative amount of SiH and SiH₂ bonds. Using this method we also obtained the total hydrogen content C_H [Eq. (3)] of the films, and their IR refractive indices n_{ir} .

For the FTIR measurements, we deposited a-Si:H films on double side polished (DSP) p -type c-Si substrates with resistivity $\rho > 1$ kΩ cm. The substrates were dipped in 1% hydrofluoric acid for 1 min prior to film deposition.

By fitting the FTIR transmission data to a transfer-matrix method calculation²¹ we obtained the n_{ir} and the absorption coefficients α of the a-Si:H films. In the fitting, we used a non-dispersive n_{ir} . We also measured the n_{ir} and α of the bare c-Si substrate, and used this to model the substrate in the calculation.

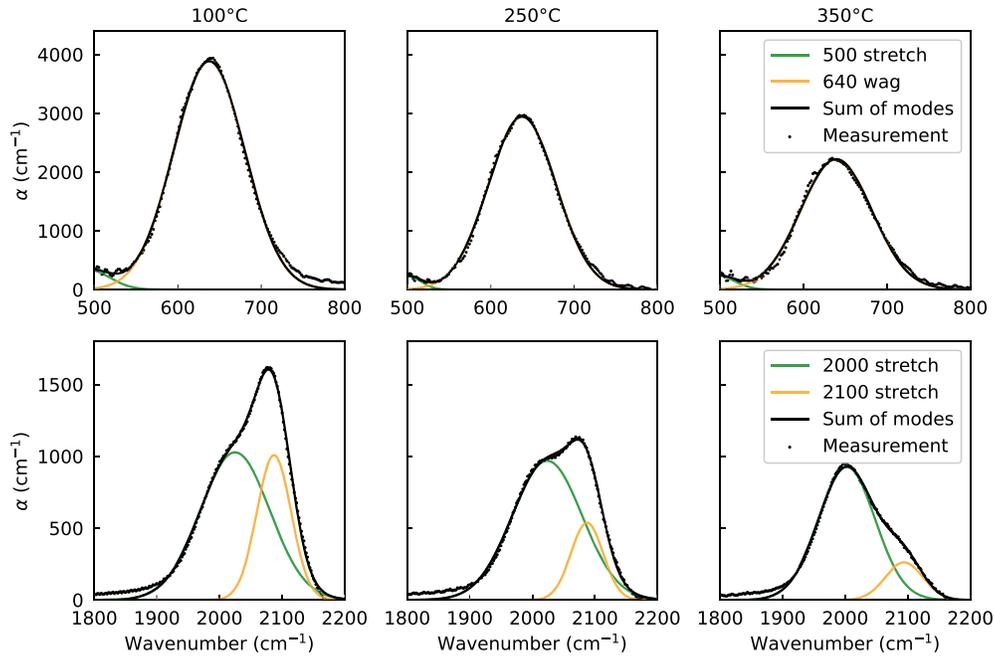


Fig. 1 The absorption coefficients α that we measured using FTIR spectroscopy, as a function of wavenumber. Each column shows the results for a particular film that was deposited at the substrate temperature T_{sub} shown on top. The top row shows the absorption near the wagging mode at 640 cm^{-1} (referred to as 640 wag), from which we calculated the hydrogen content C_H [Eq. (3)]. The bottom row shows the absorption near the stretching modes at 2000 and 2100 cm^{-1} (referred to as 2000 stretch and 2100 stretch), from which we calculated the microstructure parameter R^* [Eq. (4)].

The measured α and their Gaussian fits are plotted in Fig. 1. With increasing T_{sub} , we observe a decrease in intensity of the wagging mode near 640 cm^{-1} (referred to as 640 wag), indicating a decrease in the total hydrogen content.^{18,22} We also observe an absorption peak near 500 cm^{-1} that can be attributed to a stretching mode²³ (referred to as 500 stretch). Also with increasing T_{sub} , we observe a decrease in intensity of the stretching mode near 2100 cm^{-1} , indicating a decrease in the amount of SiH_2 bonds.

To calculate the films' hydrogen contents C_H and their microstructure parameters R^* from the α spectra we numerically calculated the integrated absorptions I_x

$$I_x = \int \frac{\alpha_x(\tilde{\nu})}{\tilde{\nu}} d\tilde{\nu}, \quad (2)$$

where x denotes the center wavenumber of the Gaussian absorption peak that is being integrated. From I_{640} we calculated C_H in atomic percent (at. %) ^{18,19,22,24}

$$C_H = \frac{A_{640} I_{640}}{A_{640} I_{640} + N_{\text{Si}}}, \quad (3)$$

where A_{640} is a proportionality constant that is an inverse cross-section for photon absorption at this wavenumber. We used the value $A_{640} = 2.1 \cdot 10^{19} \text{ cm}^{-2}$.²² For N_{Si} , the atomic density of silicon, we used the value $5 \cdot 10^{22} \text{ cm}^{-3}$. The modes near 2000 and 2100 cm^{-1} can be attributed to SiH and SiH_2 , respectively.¹⁸ The fraction of Si atoms that are bonded as SiH_3 is negligible below hydrogen concentrations of 40%.²⁵ The microstructure parameter R^* was defined as¹⁸

$$R^* = \frac{I_{2100}}{I_{2100} + I_{2000}}. \quad (4)$$

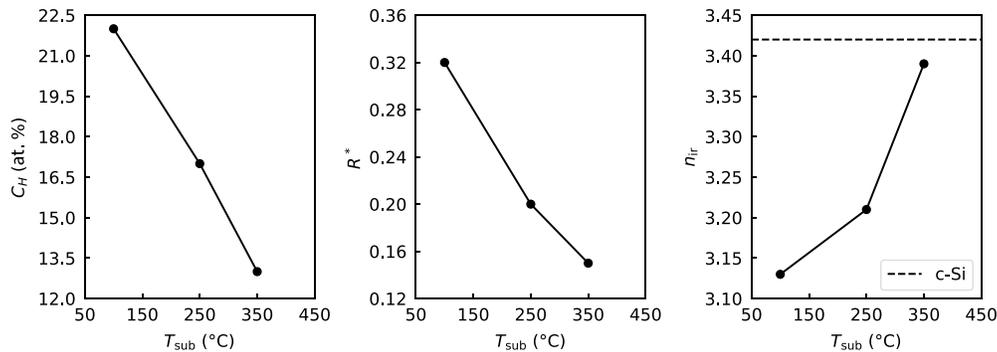


Fig. 2. The hydrogen contents C_H , microstructure parameters R^* , and IR refractive indices n_{ir} of the three films, which we derived from the FTIR data. The films were deposited at the substrate temperature T_{sub} . The dashed line in the right-most figure represents the literature value of the n_{ir} of c-Si.²²

The results for the hydrogen content C_H , microstructure parameter R^* , and IR refractive index n_{ir} are plotted in Fig. 2. We observe that C_H decreases monotonically with increasing T_{sub} . The microstructure parameter R^* also decreases monotonically with increasing T_{sub} , indicating that a smaller fraction of the hydrogen is bonded in SiH_2 configurations, which reside mostly on the surface of voids.¹⁹ Additionally, we observe that n_{ir} increases monotonically with increasing T_{sub} , indicative of an increase in film density.

3.2 Bond-Angle Disorder

Films of a-Si:H exhibit bond-angle disorder $\Delta\theta$ in their silicon network, defined as the root mean square deviation from the tetrahedral bond angle of 109.5 deg. We measured $\Delta\theta$ using Raman spectroscopy with a 514-nm laser²⁶

$$\Delta\theta = \frac{505.5 - \tilde{\nu}_{\text{TO}}}{2.5}, \quad (5)$$

where $\tilde{\nu}_{\text{TO}}$ is the center wavenumber of the transverse-optic (TO) mode near 480 cm^{-1} (TO 480).

For Raman spectroscopy, we deposited the a-Si:H films on single side polished (SSP) n -type substrates with a resistivity ρ of 1 – 5 $\Omega \text{ cm}$, and with a 101-nm thick thermal oxide layer.

In Fig. 3, we show the Raman measurement of the film deposited at 100°C, and the Gaussian fits. Apart from the TO 480 mode, we observe a transverse-acoustic (TA) mode near 170 cm^{-1} (TA 170),²⁷ a longitudinal-acoustic mode near 300 cm^{-1} (LA 300),²⁸ a longitudinal-optic mode near 425 cm^{-1} (LO 425), and at 520 cm^{-1} the TO mode of the c-Si substrate, fitted with a

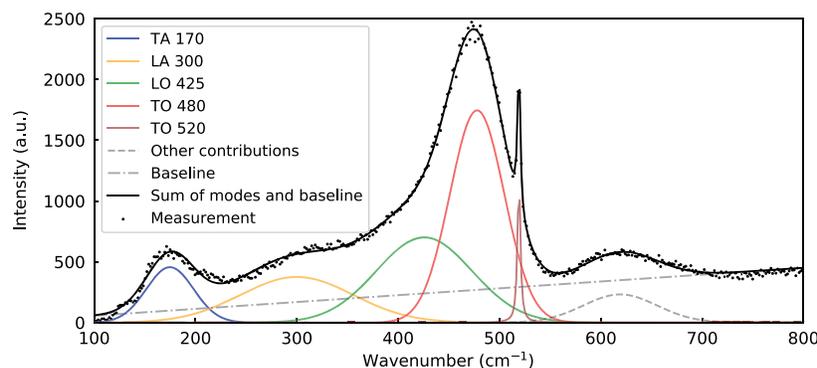


Fig. 3 The Raman spectroscopy measurement of the a-Si:H film that was deposited at a T_{sub} of 100°C. The plot serves to show the modes that are fitted to the measurement data. We calculated the bond-angle disorder $\Delta\theta$ from the position of the TO 480 mode.

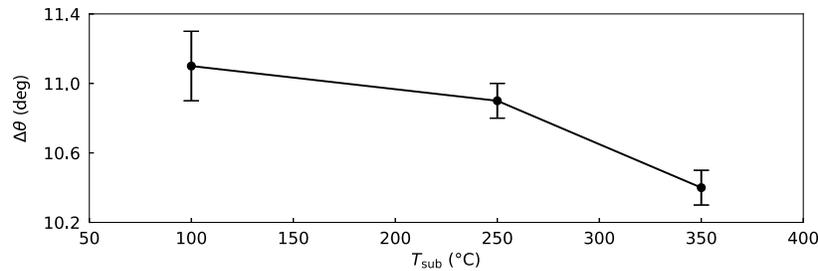


Fig. 4 The bond-angle disorder $\Delta\theta$ of the three a-Si:H films that we derived from the Raman spectroscopy measurements. The films were deposited at the substrate temperature T_{sub} . The error bars represent the standard deviations of $\Delta\theta$ that we estimated from the least-squares fit.

Lorentzian.^{26,29} The peak near 620 cm^{-1} can be attributed to a variety of modes.^{28–30} In our fit, we fixed the peak position of the LA 300 mode at 300 cm^{-1} .

We plot the measured $\Delta\theta$ of the three films in Fig. 4. We observe a monotonic decrease of $\Delta\theta$ with increasing T_{sub} .

3.3 Void Volume Fraction

We determined the films' void volume fractions f_v using variable-angle spectroscopic ellipsometry. The measured change in polarization was fitted to an optical model that includes a native oxide layer, the a-Si:H film, a thermal oxide layer, and the c-Si substrate. For this, we used the commercial software CompleteEASE.³¹

For ellipsometry, we deposited the a-Si:H films on SSP n -type substrates with a ρ of 1–5 $\Omega\text{ cm}$, with a 101-nm thick thermal oxide layer for increased reflection.

We obtained f_v from the fit by using the Bruggeman effective medium approximation to model the a-Si:H film as a composite material consisting of a-Si and spherical voids.^{13,32} The results for f_v are plotted in Fig. 5. We observe that f_v decreases monotonically with increasing T_{sub} .

4 Cryogenic Loss Tangent Measurement

4.1 Method

We fabricated superconducting chips with 109-nm-thick aluminum (Al) quarter-wavelength CPW resonators on top of the ~ 250 -nm thick a-Si:H films. To estimate the losses other than the losses due to the a-Si:H we also fabricated a chip directly on top of a c-Si substrate. The Al layer was patterned using photolithography. We deposited the a-Si:H films on DSP intrinsic c-Si substrates with $\rho > 10\text{ k}\Omega\text{ cm}$. The substrates were dipped in 1% hydrofluoric acid for 1 min prior to film deposition.

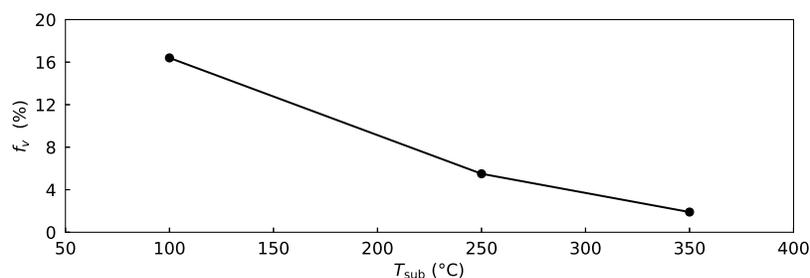


Fig. 5 The void volume fractions f_v of the three a-Si:H films, which we derived from the ellipsometry data by modeling the a-Si:H layer as a composite material of a-Si and spherical voids using the Bruggeman effective medium approximation. The films were deposited at the substrate temperature T_{sub} .

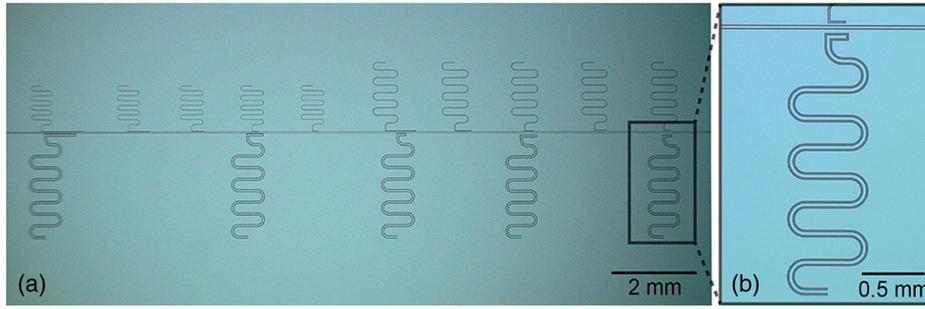


Fig. 6 (a) Micrograph of the superconducting chip. There are three groups of five quarter-wavelength CPW resonators, each group has a different CPW geometry (listed in Table 1). Within each group, the resonators vary in the coupling quality factor Q_c . (b) Zoomed-in micrograph of the bottom-right resonator in Fig. 6(a).

A micrograph of the chip with the 250°C a-Si:H is shown in Fig. 6(a). The chips feature a CPW readout line with a slot width s of $8 \mu\text{m}$ and a center line width c of $20 \mu\text{m}$. The readout line is coupled to 15 resonators. The resonators are divided into three geometry groups with different s and c . The five resonators within each group have different coupling quality factors Q_c .

We obtained the loss tangents $\tan \delta$ of the a-Si:H films at 4 to 7 GHz and at 120 mK. The cryogenic setup, which uses an adiabatic demagnetization refrigerator includes a 35-dB gain low noise (noise temperature of 3 to 4 K) high-electron-mobility transistor amplifier at the cryostat's 3-K stage, as well as two amplifiers at room temperature. The 120-mK stage is shielded from magnetic fields using a superconducting lead-tin coated shield that is surrounded by a Cryoperm shield. Further details on the cryogenic setup are given in De Visser's PhD thesis.³³ To derive $\tan \delta$, we measured the S -parameter $S_{21}(f)$ as a function of frequency using a vector network analyzer. We then obtained $\tan \delta$ from $S_{21}(f)$ by fitting the squared magnitude of the measured $S_{21}(f)$ to a Lorentzian:

$$|S_{21}(f)|^2 = 1 - \frac{1 - S_{21,\min}^2}{1 + \left(2Q \frac{f - f_r}{f_r}\right)^2}. \quad (6)$$

Here, Q is the loaded quality factor, $S_{21,\min}$ is the minimum of the resonance dip, and f_r is the resonance frequency. The internal quality factor Q_i is determined from the equality³³

$$Q_i = Q/S_{21,\min}. \quad (7)$$

For each geometry group, we used the data of the resonator that was designed for the largest $Q_{c,\text{design}} = 3 \times 10^5$ since these have the smallest fitting errors when fitting Eq. (6). The measured Q_c values vary between the different resonators in the range of $Q_c = 1.7\text{--}3.3 \times 10^5$ and the values are listed in Appendix C. The $1/Q_i$ can be expressed as

$$\frac{1}{Q_i}(g) = p(g) \tan \delta + b(g), \quad (8)$$

where g makes it explicit that these quantities are dependent on the CPW geometry. The $p(g)$ is the filling fraction of the a-Si:H film (or the c-Si substrate in the case of the c-Si reference chip), which is the fraction of the resonator's electric energy that is stored inside the dielectric.⁶ The $b(g)$ term in Eq. (8) represent the sum of all loss mechanisms other than the $\tan \delta$ of the dielectric film. We calculated the $p(g)$ using the EM-solver Sonnet,³⁴ where we used the film thicknesses t_f (listed in Appendix B), which we measured using ellipsometry, and the ϵ_{mw} listed in Table 1. The resulting $p(g)$ are visible in Table 1.

Table 1 The filling fractions p of the a-Si:H films, which we calculated using the EM-solver Sonnet.³⁴ In the case of c-Si, the p is calculated for the substrate. The ϵ_{mw} of the a-Si:H films were estimated from their IR values as $\epsilon_{\text{mw}} \approx (n_{\text{ir}}/n_{\text{cSi,ir}})^2 \epsilon_{\text{cSi,mw}}$. In the heading, s is the CPW slot width and c is the CPW center line width.

Material	CPW s - c - s (μm)		
	2-3-2	6-9-6	18-27-18
c-Si ($\epsilon_{\text{mw}} = 11.44$)	0.920	0.920	0.920
a-Si:H 100°C ($\epsilon_{\text{mw}} \approx 9.5$)	0.208	0.101	0.044
a-Si:H 250°C ($\epsilon_{\text{mw}} \approx 10.1$)	0.197	0.095	0.042
a-Si:H 350°C ($\epsilon_{\text{mw}} \approx 11.2$)	0.214	0.103	0.045

From the STM, it follows that the TLS-induced $\tan \delta$ is dependent on power, frequency, and temperature^{6,17}

$$\tan \delta = \tan \delta_0 \tanh \frac{\hbar\omega}{2k_B T} \left(1 + \frac{N}{N_0}\right)^{-\beta/2}, \quad (9)$$

where $\tan \delta_0$ is the TLS-induced loss tangent at zero temperature and low internal resonator power, N is the average number of photons inside the resonator, N_0 is the critical photon number above which the TLSs start to saturate, and β is equal to 1 in the STM, but has experimentally been found to range between 0.3 and 0.7.¹⁷ The frequency ω , the temperature T , and the photon number N are controlled by the experiment. We defined N as the average number of photons per quarter-wavelength, which is equal to $N = P_{\text{int}}/(2hf^2)$, where P_{int} is the internal resonator power, which can be calculated from the readout power.⁶

By equating the losses $b(g)$ from Eq. (8) to zero when deriving $\tan \delta$ from $1/Q_i$ we calculate an upper bound of the $\tan \delta$ of the dielectric under consideration. Additionally, we estimated the $\tan \delta$ of the a-Si:H films by equating $b(g)$ to the $1/Q_i$ of the c-Si reference chip.

4.2 Results

In Fig. 7(a), we plot the measured Q_i versus N of the resonators. We observe that Q_i increases with increasing N and that it is dependent on the CPW geometry, even for the c-Si where the filling fraction of the c-Si substrate does not depend on the CPW geometry. The filling fractions of the dielectrics are listed in Table 1.

In Fig. 7(b), we show the upper bounds of the $\tan \delta$ of the three a-Si:H films and of the c-Si substrate. The plotted $\tan \delta$ take the filling fractions of the dielectrics into account [Eq. (8)]. We observe that the a-Si:H films have an order of magnitude higher upper bound of $\tan \delta$ than the c-Si substrate. We do not observe a correlation between T_{sub} and the upper bound of $\tan \delta$. The upper bounds of $\tan \delta$ vary with the CPW geometry. For each material, the lowest values for the upper bound of $\tan \delta$ represent the overall upper bound since $\tan \delta$ is independent of geometry. We plotted the overall upper bounds as lines in Fig. 7(b). These lines are fits to a power law. From the fits, we observe that the upper bound of the $\tan \delta$ of the a-Si:H film that was deposited with a T_{sub} of 100°C has a steeper slope than the other two a-Si:H films.

The estimates of $\tan \delta$, which we calculated by using the $1/Q_i$ of the c-Si chip as an estimate for the losses other than the a-Si:H loss are plotted in Fig. 7(c). We do not observe a correlation between T_{sub} and the estimate of $\tan \delta$. The estimate of $\tan \delta$ for each material varies with the CPW geometry.

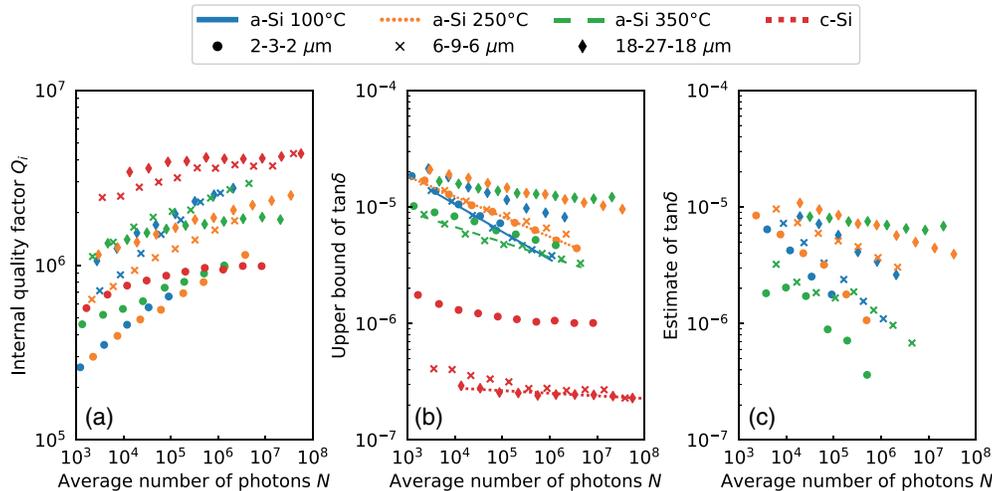


Fig. 7 (a) The measured internal quality factors Q_i of the resonators. The horizontal axis shows the average number of photons in the resonator per quarter-wavelength $N = P_{\text{int}}/(2hf^2)$, where P_{int} is the internal resonator power. (b) The upper bounds of $\tan \delta$, which we calculated by equating $b(g)$ in Eq. (8) to zero. The lines show the overall upper bounds of the $\tan \delta$ of each material and are fits to a power law. (c) The estimates of $\tan \delta$ which were calculated by equating $b(g)$ in Eq. (8) to the $1/Q_i$ of the c-Si reference chip, which has resonators directly on top of the c-Si substrate.

5 Discussion

Increasing T_{sub} results in films with less hydrogen, less voids, smaller microstructure parameter, less bond-angle disorder, and a higher IR refractive index and therefore higher film density. We have shown that changing T_{sub} is an effective way to monotonically control the structural and compositional properties of the a-Si:H. Interestingly, recent literature on electron-beam evaporated amorphous silicon suggests that the dielectric loss is correlated to the dangling bond density ρ_{DB} , which can be controlled by T_{sub} ¹⁷ as well.

Even though the structural and compositional properties at room temperature of the a-Si:H show a clear dependence on T_{sub} , we did not observe a correlation between $\tan \delta$ and the room temperature properties or T_{sub} . At the powers at which we measured, a variation in the low-power TLS-induced loss tangent $\tan \delta_0$ cannot be distinguished from a variation in the critical photon number N_0 , above which the TLSs start to saturate. However, if we assume that the three a-Si:H films have identical N_0 , then the upper bounds of $\tan \delta$ point to a low-power $\tan \delta_0$ that decreases monotonically with T_{sub} .

For the resonators with a-Si:H, it is expected that the Q_i is dependent on the CPW geometry due to differences in the dielectrics' filling fractions (Table 1). We observe that the Q_i of the c-Si resonators is also dependent on the CPW geometry even though the filling fraction of the c-Si substrate is equal for these resonators. We suggest that this is an effect due to TLS-hosting interface layers,^{35–38} whose filling fractions and therefore effect on the measured $\tan \delta$ are dependent on the CPW geometry. Furthermore, we suggest that the same effect causes the upper bound and the estimate of $\tan \delta$ to be dependent on the CPW geometry, even though here the filling fractions of the dielectrics have been taken into account. Finally, we note that in reality the c-Si chip is not a perfect reference for the $b(g)$ term in Eq. (8), which results in some estimates being higher than the overall upper bound of $\tan \delta$ [the lines in Fig. 7(b)]. This discrepancy can be explained by a different metal-dielectric surface, a different dielectric-air surface, and an additional surface between the a-Si:H film and the substrate that is not present on the c-Si chip.

The power and frequency range in which we measured is directly applicable to MKIDs, which operate at relatively high powers in comparison with the mm-submm filters that operate at single photon energies. The a-Si:H films are promising for MKID detectors because all three films exhibit an excellent $\tan \delta < 10^{-5}$ at a resonator energy of 10^5 photons per quarter-wavelength, or at -55 -dBm internal resonator power. Since the low microwave $\tan \delta$ points to

a low TLS density, it is likely that the a-Si:H films also have low loss at mm-submm frequencies.¹² Finally, we note that a practical benefit of the a-Si:H film that was deposited at 250°C is that its stress σ is close to zero, as listed in [Appendix B](#).

6 Conclusion

The structural and compositional room temperature properties of a-Si:H are monotonically controlled by changing the substrate temperature T_{sub} during deposition. We do not observe a correlation of the room temperature properties with $\tan \delta$. All three a-Si:H films exhibit a $\tan \delta < 10^{-5}$ at 120 mK and at an average photon number N of 10^5 , equivalent to -55 -dBm internal resonator power. This makes these films promising for application in mm-submm on-chip filters and MKID detectors.

7 Appendix A: PECVD Deposition Parameters

This appendix provides the PECVD parameters which we used for the deposition of the a-Si:H films (Table 2).

Table 2 PECVD parameters.

Material	a-Si:H 100°C/250°C/350°C
T_{sub} (°C)	100/250/350
RF power (W)	15
SiH ₄ flow (sccm)	25
Ar flow (sccm)	475
Pressure (Torr)	1
Deposition time (m's")	10'0"/7'9"/7'0"

8 Appendix B: Results of Characterization at Room Temperature

This appendix provides a summary of the results of the characterization at room temperature (Table 3).

Table 3 Results of the characterization at room temperature.

Film	a-Si:H 100°C	a-Si:H 250°C	a-Si:H 350°C
T_{sub} (°C)	100	250	350
C_H (at.%)	22	17	13
Microstructure parameter R^*	0.32	0.20	0.15
IR refractive index n_{IR}	3.13	3.21	3.39
Bond-angle disorder $\Delta\theta$	11.1 ± 0.2	10.9 ± 0.1	10.4 ± 0.1
Void volume fraction f_v (%)	16.5	5.6	2.0
Film thickness t_f (nm)	250.8 ± 0.1	236.0 ± 0.1	259.9 ± 0.1
Native oxide thickness t_n (nm)	5.8 ± 0.1	4.7 ± 0.1	4.2 ± 0.1
Stress σ (MPa) (tens.)	128.7	3.0	-379.0

9 Appendix C: Measured Coupling Quality Factors

This appendix provides the measured coupling quality factors of the resonators (Table 4).

Table 4 The coupling quality factors Q_c of the resonators, averaged over all readout powers. The listed uncertainties are the standard deviations in Q_c . In the heading, s is the CPW slot width and c is the CPW center line width.

Material	CPW s - c - s (μm)		
	2-3-2	6-9-6	18-27-18
c-Si	$2.83 \pm 0.04 \times 10^5$	$2.65 \pm 0.09 \times 10^5$	$1.96 \pm 0.03 \times 10^5$
a-Si:H 100°C	$1.67 \pm 0.01 \times 10^5$	$2.06 \pm 0.05 \times 10^5$	$2.00 \pm 0.06 \times 10^5$
a-Si:H 250°C	$1.76 \pm 0.02 \times 10^5$	$3.05 \pm 0.07 \times 10^5$	$3.13 \pm 0.11 \times 10^5$
a-Si:H 350°C	$3.32 \pm 0.04 \times 10^5$	$2.06 \pm 0.05 \times 10^5$	$2.98 \pm 0.10 \times 10^5$

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