# Atomic Layer Deposition for Quantum Devices

White paper

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## Introduction

As the transistor gave rise to the information age, quantum technology has the potential to be the next great leap forward. Quantum technology is the application of quantum physics for real world applications such as quantum computing, sensing, navigation and communication. Here superconducting single photon detectors (SSPDs) and superconducting qubits have been essential building blocks. The SSPDs and superconducting qubits encompass a variety of devices, including microwave resonators, transition edge sensors (TES), superconducting nanowires for single photon detectors (SNSPDs), Josephson junctions and high-Q superconducting resonators. One of the most crucial factors impacting the operation of these quantum devices is the choice and quality of the superconducting material used. It is important that the material of choice exhibits superconducting behaviour at high critical temperatures ($T_c$) in order to avoid the additional cryocooler techniques that are needed for low $T_c$ material, and that the quantum efficiency (QE) and quantum detection efficiency of these devices is maximised.[1] Furthermore, it is also important that the defects in materials used in tunnel barriers, such as in Josephson junctions, are at a minimum as these could lead to decreased coherence of the qubit.[2]

Conventional methods for depositing superconductors include sputtering, pulsed laser deposition (PLD) and chemical vapour deposition (CVD). However, these methods can suffer from drawbacks including a lack of thickness control, poor uniformity and high impurity content. Atomic layer deposition (ALD) is much more beneficial for thin-film deposition due to its ability to produce films with high purity, precise thickness control, conformal coating in high aspect ratio structures and uniformity over large-area substrates. ALD has already successfully been applied in many fields such as in CMOS technology, high-power transistors, solar cells and many more.

An emerging application is for films in devices for quantum applications. Illustrated on Figure 1 are examples where superconducting material has been integrated on to quantum nanophotonic circuitry. Figure 1(a) uses a 4 nm thick NbN nanowire folded in a meander pattern on a Si substrate with a 160 nm layer of $SiO_2$.[3] and 1(b) consists of a silicon waveguide where the detection region is covered with NbN.[4]

Other nitrides such as TiN may also be a possible candidate for integration in such circuitry. In this whitepaper we focus on the potential of such superconducting nitrides by ALD.

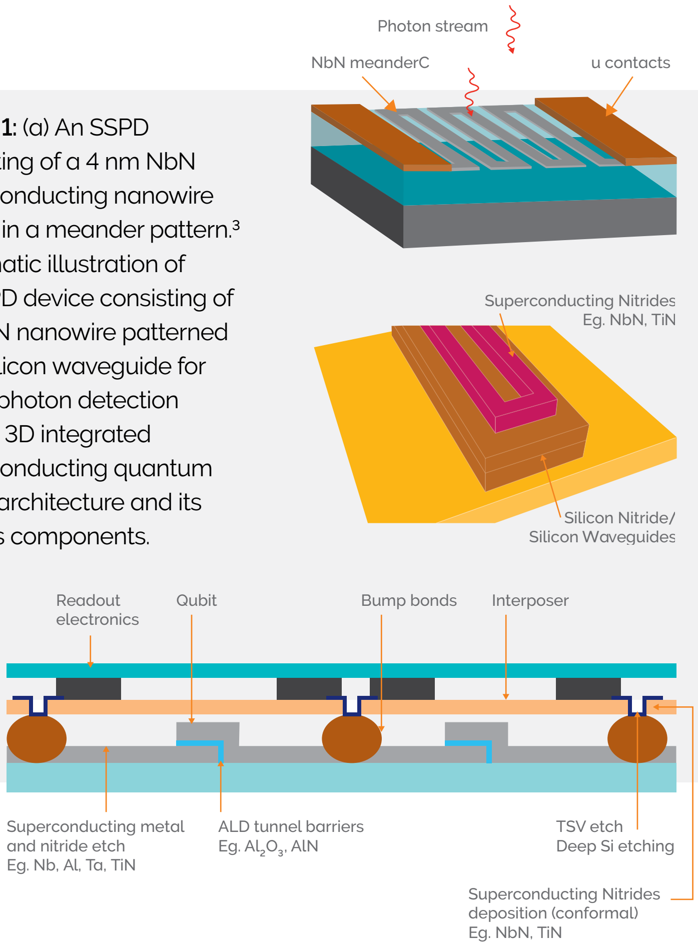

**Figure 1:** (a) An SSPD consisting of a 4 nm NbN superconducting nanowire folded in a meander pattern.[3] Schematic illustration of (b) SSPD device consisting of an NbN nanowire patterned on a silicon waveguide for single photon detection and (c) 3D integrated superconducting quantum circuit architecture and its various components.

# Atomic layer deposition for quantum applications

The aforementioned characteristics of ALD are achieved by sequentially exposing the precursor and the reactive gas to the substrate in separate stages with a purge after each exposure; resulting in precise thickness control and films with high purity. A wide variety of materials ranging from metals to nitrides and oxides have been deposited using either thermal or plasma ALD.[5] Further, ALD offers a large parameter space which can be tuned to deposit films with the desired qualities. Specifically, in plasma ALD additional parameters such as plasma power, pressure and reactant flow rate give more flexibility in optimising film properties.

Additionally, in Plasma ALD the film properties can be further improved by biasing the substrate during deposition. As illustrated on Figure 2, by varying the bias, the energy of the ions generated in the plasma can be tuned to enhance film qualities such as refractive index (RI), conductivity, crystallinity and stress.[6] The bias can be applied for the total duration of the plasma or it can be applied for a proportion of the plasma exposure time.

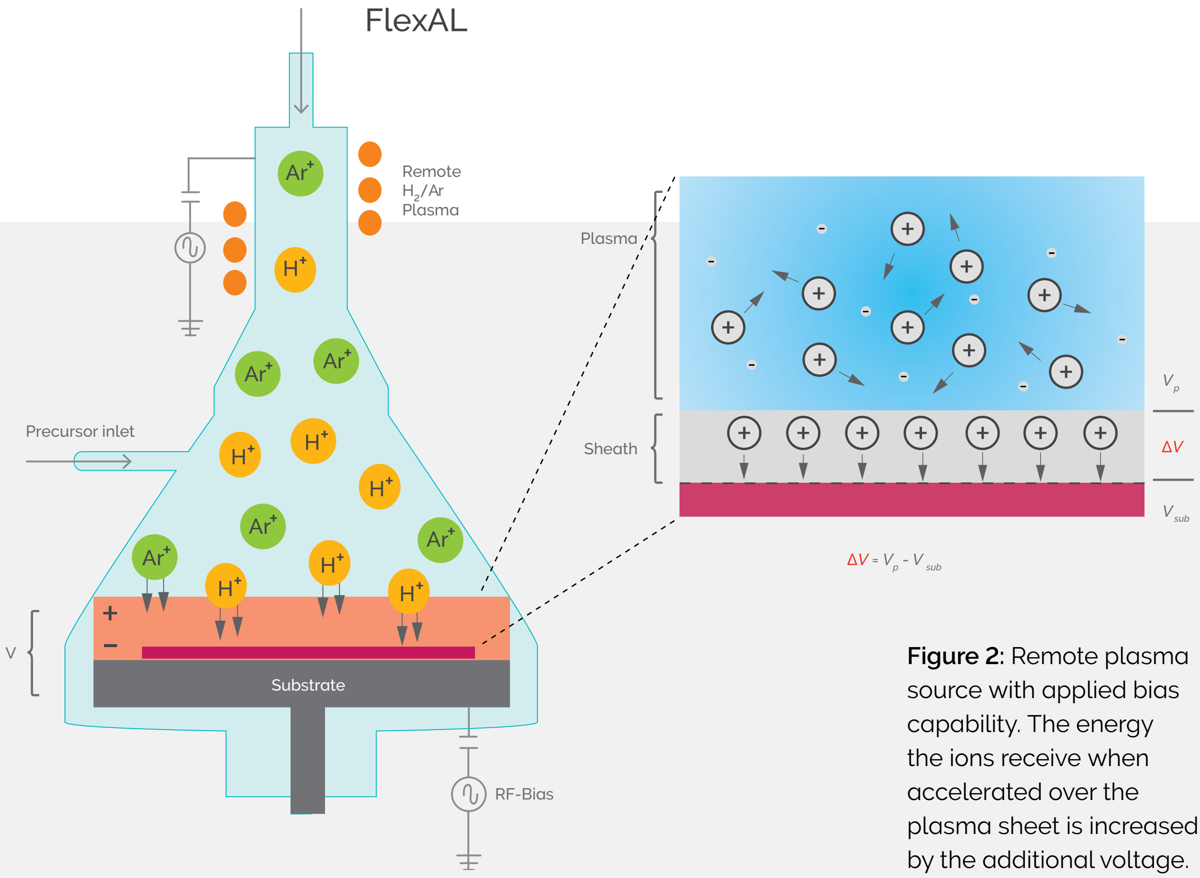

**Figure 2:** Remote plasma source with applied bias capability. The energy the ions receive when accelerated over the plasma sheet is increased by the additional voltage.

## Materials for quantum applications

Refractory metal and metal-based nitrides have been used as the foundation materials for superconducting detectors.[7] Plasma ALD has been the preferred choice over thermal ALD for depositing these materials due to its advantages such as reduced deposition temperature, improved film properties, better nucleation and a greater number of film composition options.[8] NbN and NbTiN have been the most widely used superconducting materials deposited by ALD due to their favourable $T_c$s.

NbN has been deposited by Plasma ALD using TBTDEN and $H_2$ as well as TBTDEN and $N_2/H_2$ plasma.[8,9] It has been demonstrated that by varying the substrate temperature and plasma gas flow rate during deposition, the superconducting transition temperature and room temperature resistance can be optimised. The optimised process has produced films with a $T_c$ of 13.7 K.[8]

NbN film properties can also be improved by varying the bias applied to the substrate. The effect of a bias power applied when depositing NbN films on the room temperature resistivity and films stress is shown on Figure 3. It can be observed that the bias power had an impact on these parameters and a strong correlation exists between resistivity and film stress. A minimum room temperature and film stress were obtained at a bias power of 12 W.[10] The resistance as a function of temperature is shown in Figure 4 for a film deposited at 12 W bias power and at a temperature of 250 ˚C. A $T_c$ of 12.9 K has been achieved for for the film deposited at 250 ˚C with a bias power of 12 W.[10] These measurements were performed by Oxford Instruments Nanoscience. Shown on Figure 5 is the effect on R.T. resistivity as a function of deposition temperature of the film with the applied bias at 12 W. It can be observed that the films grown using bias have R.T. resistivity values below 300 µ.cm for temperatures ranging from 120 ˚C to 300 ˚C. Low R.T resistivity values have therefore been achieved at low deposition temperatures with the application of a bias. The film grown without bias also used a longer plasma exposure time of 50 s while the biased films had less than half the plasma exposure time of 20 seconds.[11] Therefore the films can also be grown faster when applying substrate bias.

Sputtered NbTiN has also demonstrated potential to be used as a superconducting film for quantum applications due to its reported favourable bulk $T_c$ 18 K.[12,13] ALD could be a better approach of depositing NbTiN using TBTDEN and TDMAT precursors and $N_2/H_2$ plasma. The film properties can be further optimised by tuning the film composition of NbTiN by varying the TBTDEN: TDMAT cycle ratios.

Despite the favourable $T_c$ demonstrated for NbN and NbTiN films, the material photon sensitivity drops when detecting wavelengths beyond 2 µm.[6] Lower superconductivity gap materials such as TiN have also been widely researched despite its lower $T_c$ due to its greater sensitivity at longer wavelengths.[6] TiN can be deposited using TDMAT and $N_2/H_2$ plasma. Illustrated in Figure 6 is an optical image of microwave kinetic inductance detectors (MKIDs) that have been produced using ALD TiN.[14] Table 1 summarises the data obtained for various thicknesses of TiN. This work which was performed without application of table bias achieved a maximum $T_c$ of 2.4 K at thicknesses of 30 nm. These properties can be further improved by optimising the process parameters and applying a bias power.

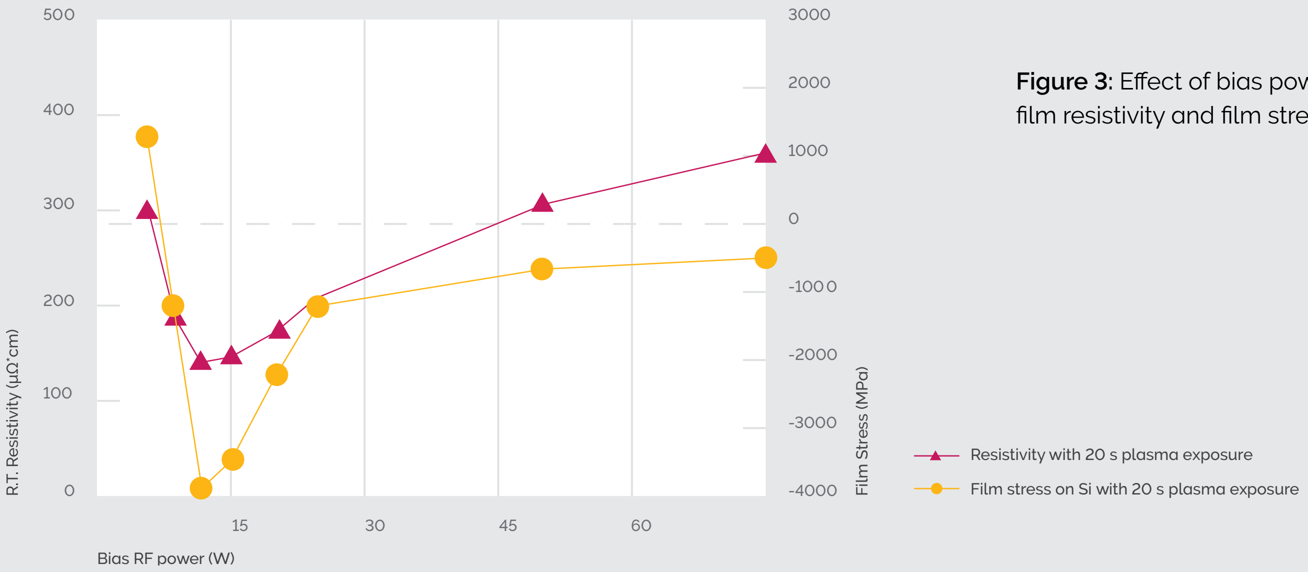

**Figure 3:** Effect of bias power on film resistivity and film stress.

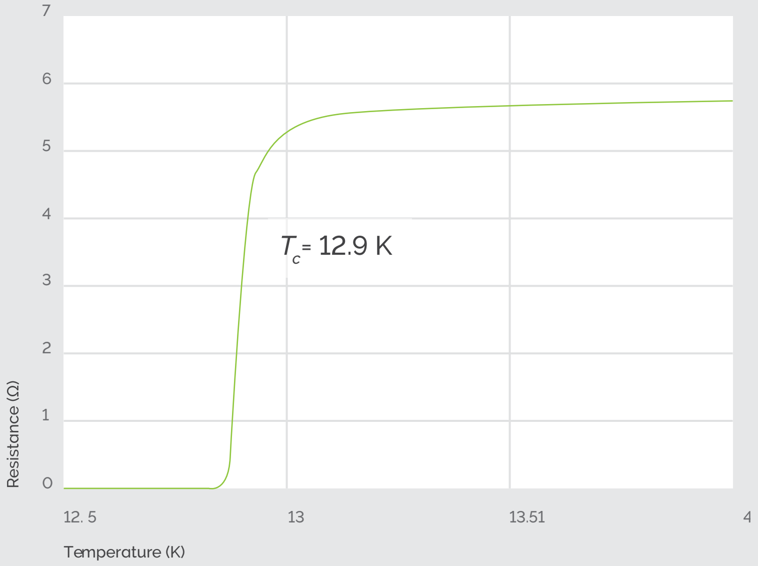

**Figure 4:** Resistance versus temperature plot for for film deposited 250 ˚C, with 20 s plasma exposure and 12 W applied bias power.

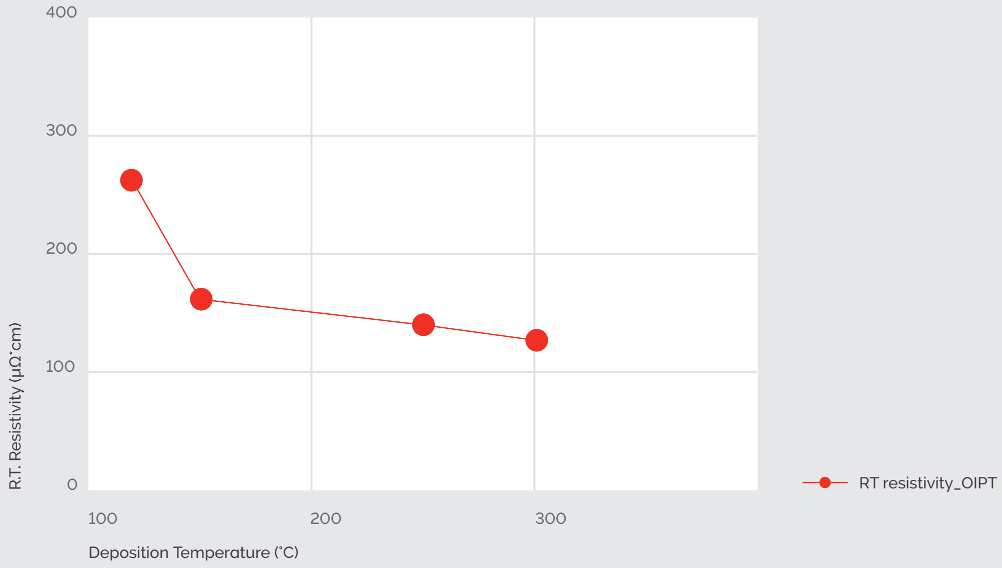

**Figure 5:** R.T. resistivity versus deposition temperature of plasma ALD NbN films with an applied bias.

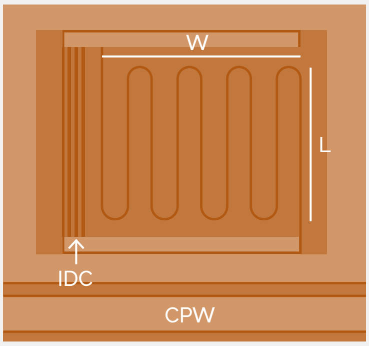

**Figure 6:** A TiN based microwave resonator used in a kinetic inductance based ThZ detector application.[14]

| Film | d(nm) | *p*(μΩcm) | $R_s$ (Ω/sq) | $T_c$(K) |
|---|---|---|---|---|
| ALD1 | 30 | 449 | 149 | 2.4 |
| ALD2 | 30 | 432 | 139 | 2.09 |
| ALD3 | 15 | 270 | 180 | 2.04 |
| ALD4 | 60 | 295 | 43.5 | 2.06 |

**Table 1:** Effect of TiN thickness on film resistance and $T_c$.

In addition to ALD of nitrides, oxides such $Al_2O_3$ could also be beneficial for superconducting qubit circuits that employ Josephson junctions. Defects in the dielectrics used in tunnel barriers in Josephson junctions can give rise to decoherence in these junctions. Plasma ALD $Al_2O_3$ is therefore advantageous due to its low defect density and can be applied to future devices.[2]

## Conclusion

The properties of the materials used to produce quantum technology is of paramount importance to its operation. It has been shown that ALD can allow for fine control of these properties such as composition, resistance, $T_c$ and film stress. Thus, ALD can be a driving force behind the development of technologies for quantum applications and the ability of Oxford Instruments' ALD tools to apply a bias during processes could be a route to further enhance the materials used in quantum technology.

## Acknowledgements

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