論 文 の 内 容 の 要 旨

論文題目　　Direct fabrication of superconducting nanodevices
by using FIB-CVD
（FIB-CVDを用いた超伝導ナノデバイスの直接作製法）

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## １．Research background

The quantum properties of mechanical detectors will impose ultimate limits on their force sensitivity. The integration of superconducting devices acts as control and detection elements in nanoelectromechanical systems (NEMS). Combinations of superconductivity and NEMS have great potential in improving the precision, performance, and developing novel functions of nanomechanical resonators. Furthermore, operating and observing the quantum behavior of nanomechanical resonators will make greatly contribution to future quantum devices, quantum information computing, spintronics, biological science, medical science and so on.

However, obstacles for flexible design and also free 3D structure fabrication still exist since these superconducting nanomechanics devices are still fabricated by traditional indirect fabrication methods, such as resist based lithography, etching process and liftoff process.

In order to realize high precision, high performance, and also develop novel functions for integrated sensors, fabrication technologies, allowing free combination of resonators and superconducting circuits, high flexibility in 3D structure of resonators for the combination, are necessary.

**2. Research purpose**

The largest motivation is to realize direct combination of superconducting circuits and 3D structure or nanomechanical resonator by using focused-ion-beam chemical-vapor-deposition (FIB-CVD). This research will further dedicate to high performance SQUID sensors, nanomechanical systems, providing significant tools for fundamental low temperature physics and quantum information technologies. Specifically, the purposes of this research mainly include:

1. To investigate characteristic of FIB-CVD based superconducting materials that has not been studied sufficiently.
2. To search for superconducting materials suitable for 3D fabrication.
3. To realize high controllability of FIB-CVD for superconducting devices.

**3. Research contents**

**3.1 Superconductivity in W-C nanowires grown by FIB-CVD**

Since superconducting nanowires are the basic components for superconducting circuit, FIB-CVD based W-C nanowires are used to study the electrical property of FIB-CVD based materials.

The temperature dependence of normalized resistance ($R/R_{300K}$) of nanowires deposited from $W(CO)_6$ and $C_{14}H_{10}$ is shown in Fig. 1.

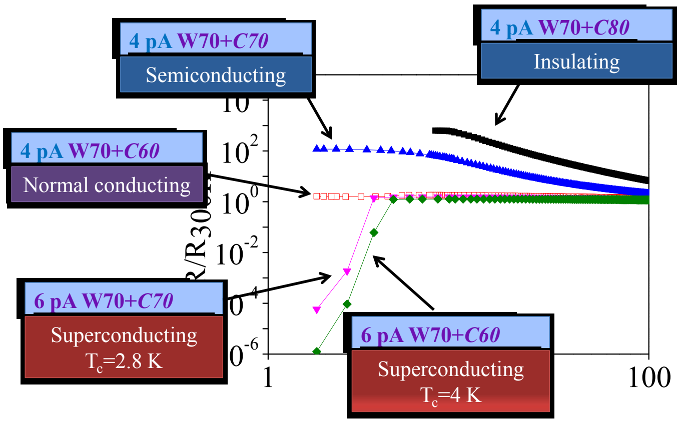



Fig. 1 Temperature dependence of the normalized resistance of W-C nanowires deposited from the mixture of $W(CO)_6$ and $C_{14}H_{10}$.

For W-C nanowires grown at $I_{Ga+}$ = 4 pA, when $C_{14}H_{10}$ precursor temperature is set at 60°C, the deposited W-C nanowire shows metallic behavior. As $C_{14}H_{10}$ precursor temperature increases to 70°C and 80°C, the deposited W-C nanowires show “semiconducting / insulating” like behaviors. For W-C nanowires grown at $I_{Ga+}$ = 6 pA, when $C_{14}H_{10}$ precursor temperature is set at 60°C and 70°C, the deposited W-C nanowires show superconductivity with $T_c$ of 4.0 K and 2.8 K, respectively. As $C_{14}H_{10}$ precursor temperature increases to 80°C, the deposited W-C nanowire shows "semiconducting / insulating" like behaviors. For W-C nanowires grown at $I_{Ga+}$ = 10 pA, with $C_{14}H_{10}$ precursor temperature set at 60°C, 70°C and 80°C, the deposited W-C nanowires show "semiconducting/insulating" like behaviors. Therefore, we realized the free tuning of electrical property of materials.

**3.2 Investigation of growth rate of superconducting nano pillars**

Superconducting, free-standing W-C nano pillars have been deposited solely by $W(CO)_6$ precursors (Fig. 2(a)) for 5 s, 10 s, 15 s, 20 s, 25 s, and 30 s. We also show free-standing W-C nano pillars deposited with the addition of $C_{14}H_{10}$ precursor for 5 s, 10 s, 15 s, 20 s, 25 s, and 30 s. ($I_{Ga+}$ = 6 pA), as shown in Fig. 2(a). Without the aid of $C_{14}H_{10}$, the growth rate of W-C nano pillar is 0.8 μm/min, whereas 3.4 μm/min can be reached with aid of $C_{14}H_{10}$ (70°C). By introducing $C_{14}H_{10}$ into $W(CO)_6$ during the deposition process, the growth rate was enhanced significantly. And this growth rate greatly facilitates the fabrication of three-dimensional superconducting structure.

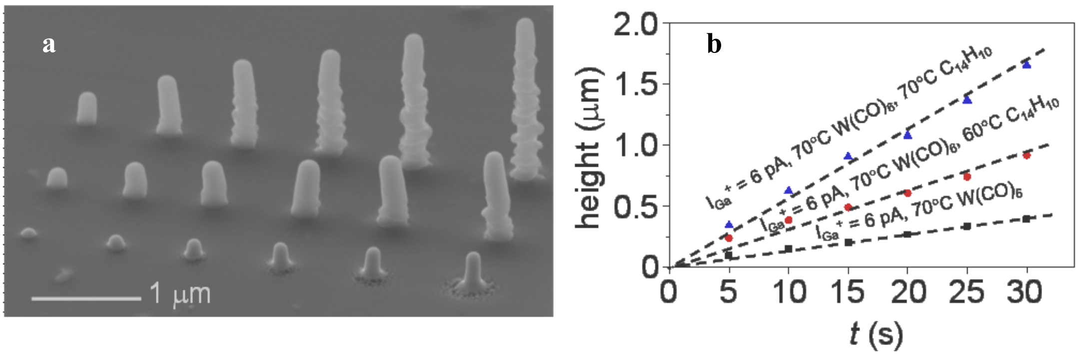
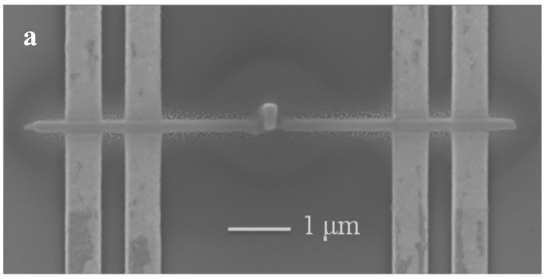



Fig. 2(a) The SEM image of W-C nano pillars deposited from FIB-CVD. (b) The height of W-C nano pillars as a function of deposition time under various conditions.

**3.3 FIB-CVD based superconducting SNS Josephson junction**

We also demonstrated that this novel technology could be used to realize free combination of materials for the basic component of superconducting circuits–Josephson junction. The precursor $W(CO)_6$ (70°C) with Ga ion beam current of 1 pA was used to deposit the superconducting electrodes. It is demonstrated that W-C nanowire fabricated by this condition show superconductivity with $T_c$ of 4.6 K. The metallic junction is deposited from the precursor of $W(CO)_6$ and $C_{14}H_{10}$ with Ga ion beam current of 4 pA. In order to confirm the supercurrent in our junction is Josephson current, an in-plane external magnetic field is applied. The magnetic field is applied from 0 to 0.8 T with a step of 0.01 T. The *V-I* curves of both samples were measured at each step. The critical current in response to the applied field is also shown in Fig. 3(b). A Fraunhofer-like oscillation of the critical current in the SNS Josephson junction is clearly observed.



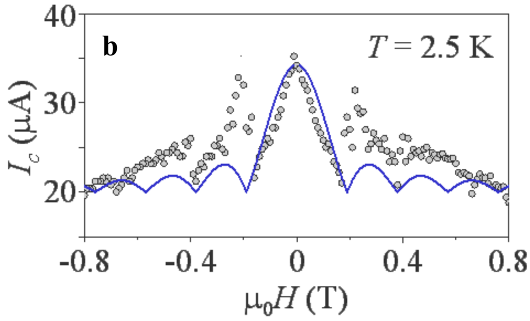




Fig. 3 (a) The SEM image of a SNS Josephson junction fabricated by FIB-CVD (b) A Fraunhofer-like oscillation of this SNS Josephson junction.

## 4. Conclusions

The thesis is dedicated to develop a direct fabrication technique for superconducting nanodevices. The main conclusion of this research is shown as follows:

Superconductivity in FIB-CVD based W-C nanowires was demonstrated by using $W(CO)_6$ and the mixture of $W(CO)_6$ and $C_{14}H_{10}$ as precursors. $T_c$ of superconducting nanowires is from 2.8 K to 5.8K. Also, the origin of superconductivity in FIB-CVD based W-C nanowires was discussed by using Osofsky model for the disordered system. The fitting results show that superconductivity in FIB-CVD based W-C nanowires could be well explained by Osofsky model.

Free combination of superconducting, normal conducting and insulating material is realized through the synthesis of W-C nanowires with mixtures of $W(CO)_6$ and $C_{14}H_{10}$ by FIB-CVD. Freestanding W-C nano pillars were grown by FIB-CVD. The growth rate of the deposition from the mixture is at most 4.25 times higher than $W(CO)_6$ is used as the precursor. This growth rate greatly facilitates the fabrication of three dimensional superconducting structures.

Direct fabrication technology for W-C SNS Josephson junctions by FIB-CVD was developed. A Fraunhofer oscillation of critical current, with the period of 0.19 T was observed, which is consistent with the estimated value. Coherence length $\xi_N$(2.5 K) in metallic W-C material is estimated as 270 nm.