Silicon Nanotubes as Drug Delivery Vectors

Nguyen Le, Jeffery L. Coffer*
Department of Chemistry and Biochemistry, Texas Christian University, TX, 76109

I. NTRODUCTION

Semiconducting silicon (Si) is a promising element that has been extensively studied in various fields ranging from microelectronics to bio-relevant applications.[1] In fact, nanostructured porous silicon has received widespread attention due to its unique chemical and physical characteristics.[1] Another relatively more well-defined example of nanostructured silicon is Si nanotubes (SiNTs) with well-characterized sidewalls, inner void space and lengths, allowing opportunities to study its potential properties in diverse fields, particularly drug delivery. The available interior free space of the NTs offer the material the ability of confining a desired amount of payload of therapeutic agents. Moreover, the available silanol groups on the surface of the NTs also enable attachment to a linker, ex. 3-aminopropyltriethoxysilane (APTES) with amino group on the other end is subsequently attached to a drug molecule of interests.

In this drug delivery study, in order to enhance the therapeutic effect of a cancer therapeutic agent, known as cisplatin, SiNTs are employed as drug delivery vectors. In particular, SiNTs with lengths less than 1 μm are synthesized (for optimal cellular uptake), and a sidewall thickness ~ 10 nm for desirable dissolution within a biological environment. For the purpose of controlling the loading and release of the drug, SiNTs are functionalized with APTES and subsequently loaded with drug molecules.

II. EXPERIMENTAL PROCEDURES AND RESULTS

A. Synthesis of Silicon Nanotubes

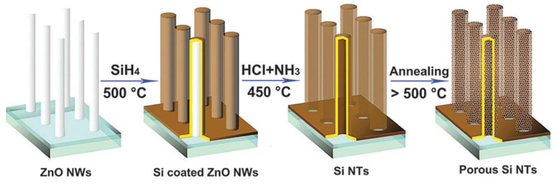

Figure 1. Synthesis scheme of Silicon nanotubes[2]

1. Growth of ZnO NWs at 95°C
2. Deposition of Si on ZnO core via chemical vapor deposition of SiH_4

$$SiH_4 \rightarrow Si\ (g) + 2H_2\ (g)$$

3. Removal of ZnO core from ZnO-Si composite to produce hollow SiNTs

$$ZnO + 2HCl \leftrightarrow ZnCl_2 + H_2O$$
$$ZnCl_2 + NH_3 \leftrightarrow Zn(NH_2)Cl + HCl$$

4. (Optional) Enhancement of crystallinity of SiNTs via annealing

B. Control Silicon Nanotube Length

For optimal cellular uptake, the length of SiNTs needs to be less than 1 μm.

The length of SiNTs can be controlled by modulating the growth time of ZnO NWs.

Table 1. Growth time of ZnO NWs and lengths of the resulting SiNTs

	Growth time of ZnO (hrs)	Length (μm)
A	1.5	0.3 - 0.5
B	3	1.5 - 2.0
C	6	2.5 - 3.0
D	9	3.0 - 3.5

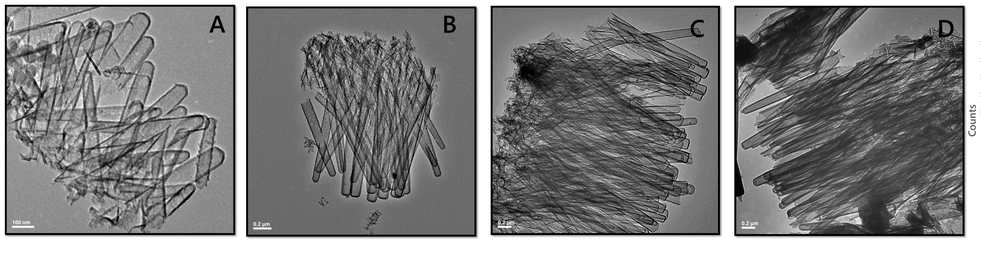

Figure 2. SiNTs of different lengths. A. 0.3 - 0.5 μm, B. 1.5 – 2.0 μm, C. 2.5 – 3.0 μm and D. 3.0 – 3.5 μm.

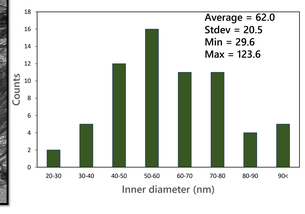

Figure 3. Inner diameter of SiNTs with length of 0.3-0.5 μm.

B. Functionalization of Silicon Nanotubes with 3-aminopropyltriethoxysilane (APTES) and Reaction with Cisplatin

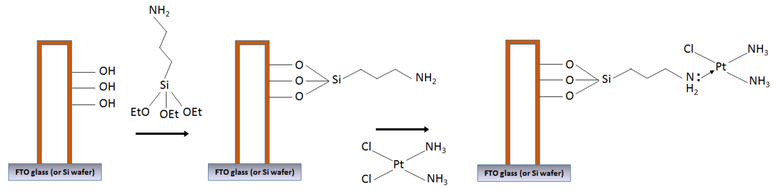

Figure 4. Reaction scheme for APTES functionalization and Cisplatin coordination to APTES-functionalized SiNTs.

In the presence of water, triethoxy group of APTES is hydrolyzed to become hydroxyl group, which is covalently bonded to the silanol groups on the Si surface. Therefore, the amino group on the other end of the aminopropylsilane (APS) can be used to coordinate with other molecules.

C. Coordination of Cisplatin to APTES-functionalized Silicon Nanotubes

Table 2. Conditions of APTES functionalization and the corresponding amounts of cisplatin coordinated to APTES-functionalized SiNTs

	Solvent	APTES functionalization time (hrs)	Weight %	
			Pt	Cl
A	Acetone	4	22.0 ± 2.0	0.5 ± 0.4
B	Toluene	4	34.2 ± 4.9	1.2 ± 0.8
C	Toluene	24	42.3 ± 10.3	2.0 ± 1.2

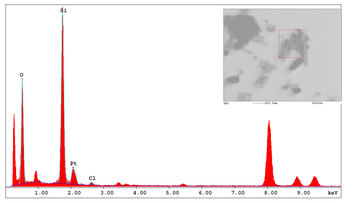

Figure 5. TEM EDX of SiNTs loaded with cisplatin (4h APTES functionalization, solvent: toluene)

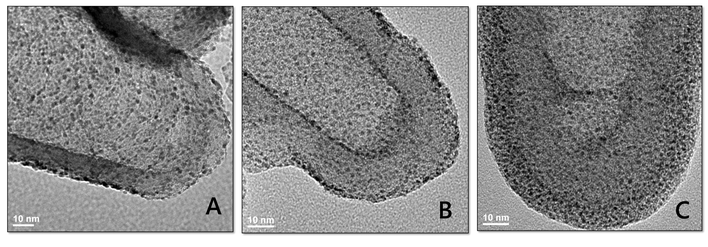

Figure 6. APTES-functionalized SiNTs loaded with cisplatin. Note: Dark spots are associated with regions of high Pt concentration.

- TEM imaging and TEM EDX analysis showed that SiNTs (length ~0.5 μm, inner diameter: ~50 nm) functionalized with APTES can be loaded with cisplatin, suggesting coordination between the drug molecule and the amino group on the coupling agent.
- By varying functionalization conditions (solvent, reaction time), the amount of cisplatin loaded into APS-SiNTs can be varied.

III. CONCLUSIONS

The results indicate that the length of SiNTs can be readily controlled by varying the time of ZnO growth. For bio-relevant applications, the length of less than 1 μm can be achieved. In addition, methods of loading cisplatin into SINTs have been developed. Future works involve biological studies with cancer cells will be performed in order to evaluate therapeutic effects of the cisplatin-SiNTs composites.

IV. REFERENCES

1. Canham, L.T. *Hanbook of Porous Silicon*. Switzerland: Springer International Publishing AG, 2014.
2. Huang, X.; Gonzalez-Rodriguez, R.; Rich, R.; Gryczynski, Z.; Coffer, J. L. *Chem. Comm*, 2013, 49, 5760-5762.

V. ACKNOWLEDGEMENTS

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