# Unusual 2-D Electron Gas at the Surface of Square $SnO_2$ Nanotubes

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Tin dioxide ($SnO_2$) is an earth-abundant, technologically-important, transparent semiconducting oxide with a range of useful properties such as a wide bandgap, strong *n*-type conductivity, and a high surface electron density, that enable a wide range of electronic, gas sensing, and catalytic applications. A wide range of low-dimensional $SnO_2$ nanomaterials have also been reported with most of these possessing conventional circular and cylindrical geometries [1].

In contrast, we have developed a highly-scalable method of synthesising arrays of $SnO_2$ nanotubes with perfectly-square geometries on Au-nanoparticle coated sapphire, quartz, and silicon substrates using mist chemical vapour deposition [2]. These square nanotubes have a unique geometry, exhibit a high single crystallinity, and can be controllably doped with Sb with no loss in structural quality (Fig. 1a,b).

Furthermore, we have used synchrotron x-ray photoelectron spectroscopy to reveal the presence of an unusually strong and thermally resilient 2-dimensional electron gas (2DEG) on the (110) surfaces of these nanotubes (Fig. 1c). We show that this 2DEG is created by donor-like states produced by the hydroxyl termination of the (110) surface and is sustained at temperatures above 400 °C by the formation of in-plane oxygen vacancies. This persistent high surface electron density is expected to prove useful in gas sensing and catalytic applications of these remarkable structures.

We also demonstrate that the strength of the 2DEG can be modified by different surface treatments, in particular the electrografting of 4-nitrophenyl layers and the spontaneous grafting of octadecylphosphonic acid molecules [3], a finding that represents an important step towards tuning the surface properties of these structures for different applications. To illustrate their device potential, we have fabricated single square $SnO_2$ nanotube Schottky diodes (Fig. 1d) and field effect transistors with excellent performance characteristics.

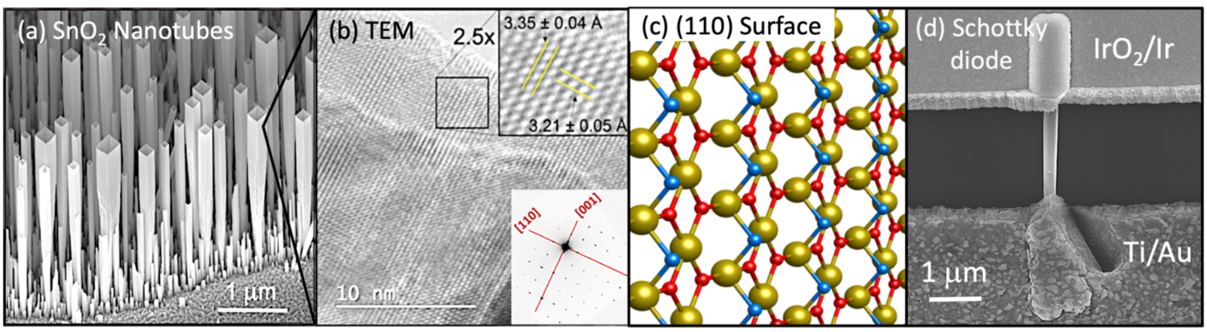


Fig. 1. (a) Square $SnO_2$ nanotubes on m-plane sapphire, (b) TEM image from the top of a nanotube, (c) atomic structure of the (110) sidewalls (Sn atoms in gold, in-plane O in red, bridging O in blue), (d) Schottky diode.

[1] X. Wang *et al.*, Chemistry of Materials, **26**, 123 (2014)
[2] J.I. Scott *et al.*, Small, (2023, in press)
[3] L.R. Carroll *et al.*, ACS Applied Electronic Materials, **3**, 5608 (2021)