Comment on "Ultrahigh secondary electron emission of carbon nanotubes" [Appl. Phys. Lett. 96, 213113 (2010)]

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Luo *et al.*[1] scanned with a 1 keV electron beam an oxidized silicon substrate partially covered with single-walled carbon nanotubes (SWNTs). They observed a higher average specimen current when the scanned area contained SWNTs connected to the silicon. Thence by multiplying this increase by the ratio of the length of the scanned area over the SWNT diameter, they deduced that SWNTs connected to a reservoir have a secondary electron emission coefficient (SEEC) of up to 123, far higher than expected based on existing reports on the interaction of electron beams with carbon nanotubes (CNTs) and their scanning electron microscopy.[2–9]

The analysis presented by the authors of Ref. 1 does not take into account the effect of the SiO_2 film underneath the CNTs adequately. For example, a more likely explanation for their measured data is that the increased secondary current is due to CNTs providing a conductive path and thus enhancing secondary electron (SE) emission from the surrounding oxide within the electron-beam-induced current range, which is much larger than the CNT diameter even at 1 keV.[4,5]

A measurement of SE emission from CNTs on a substrate should feature carefully chosen conditions (scan rate and current sampling, filtering, and averaging) and synchronize the current sampling with the scan so as to ensure that the electrometer takes enough samples when the beam hits the CNT. No such detail was given by the authors. These issues become all the more critical given that the claimed high yield is a product of the difference of very small leakage currents (only 2%–5% of the primary beam current) and a very large scan length compared to the CNT diameter [Eq. (1) in Ref. 1]. Ideally one should measure the SE current from a CNT that is freestanding over a region of negligible SEEC where bombarded with electrons.[9]

The authors suggested that the claimed high value of SEEC can be explained by the primary electron raising the highest occupied molecular orbital (HOMO) above the vacuum level. But such a drastic raise of the HOMO applies to the CNT tip in the presence of a strong external electric field.[6] Although a similar (albeit much lower) raise could partially explain SE emission from CNTs, it does not support the idea of such a high intrinsic SE yield.[6,7,10]

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A 1 keV primary beam perpendicular to a CNT is likely to pass through it without encountering significant scattering: on average the primary electron loses less than 50 eV going through the CNT.[10,11] Since for carbon it has been reported that an average energy loss of 80–125 eV by a primary electron is needed in order to generate one SE,[12,13] the <50 eV loss cannot explain an SE yield of more than 1.

The authors claimed that there was no oxide surface charging when they observed zero specimen current at 1 keV primary landing energy. This clearly cannot be the case; it is well known that in the absence of leakage an insulator whose secondary emission coefficient is greater than 1 (the authors quoted 1.18)[1] will charge to a potential at which enough SEs return to the surface to balance the incoming and outgoing electrons.

In summary, we believe that the high SEEC reported in Ref. 1 is an artifact of the analysis of the experimental data. Although the data appear to be correct, the conducted experiment was not capable of revealing the SE yield of CNTs, and the results presented do not support the claim of high SEEC.

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