OneD BATTERY SCIENCES

SINANODE® REDEFINING EV BATTERIES

SINANODE® Materials: Evaluation And Cell Design

INTRODUCTION

Purpose of this document is to provide a practical framework to evaluate SINANODE® anode materials and to design SINANODE® cells for commercial production. This document is a high-level overview and is not meant to be exhaustive. More technical details and support are available under NDA to companies interested in receiving samples of the SINANODE® materials for testing and evaluation purposes

1. Types of SINANODE® materials:

SINANODE® is a brand name that refers to a variety of materials all consisting of silicon nanowires grown on graphite powder. The SINANODE® materials are broadly characterized by three key parameters: (1) the graphite substrate selected to grow silicon nanowires; (2) the catalyst used to convert silane into nanowires; and (3) the weight percentage of silicon in the finished graphite-silicon nanowire composite powder.

The silicon nanowires in SINANODE® are grown directly onto the graphite particles using a Chemical Vapor Deposition ("CVD") process, in which silane (SiH_4) gas reacts with catalyst nanoparticles deposited onto the surface of the graphite particles.

The graphite substrate in SINANODE® is typically a commercial graphite already in use in the battery industry. OneD has grown silicon nanowires on most of the best commercially available graphite active materials, without any necessary modification. For example, OneD has successfully tested in Lithium-ion batteries SINANODE® materials produced using different types of Hitachi graphite ranging from MAG-D to MAG-E series.

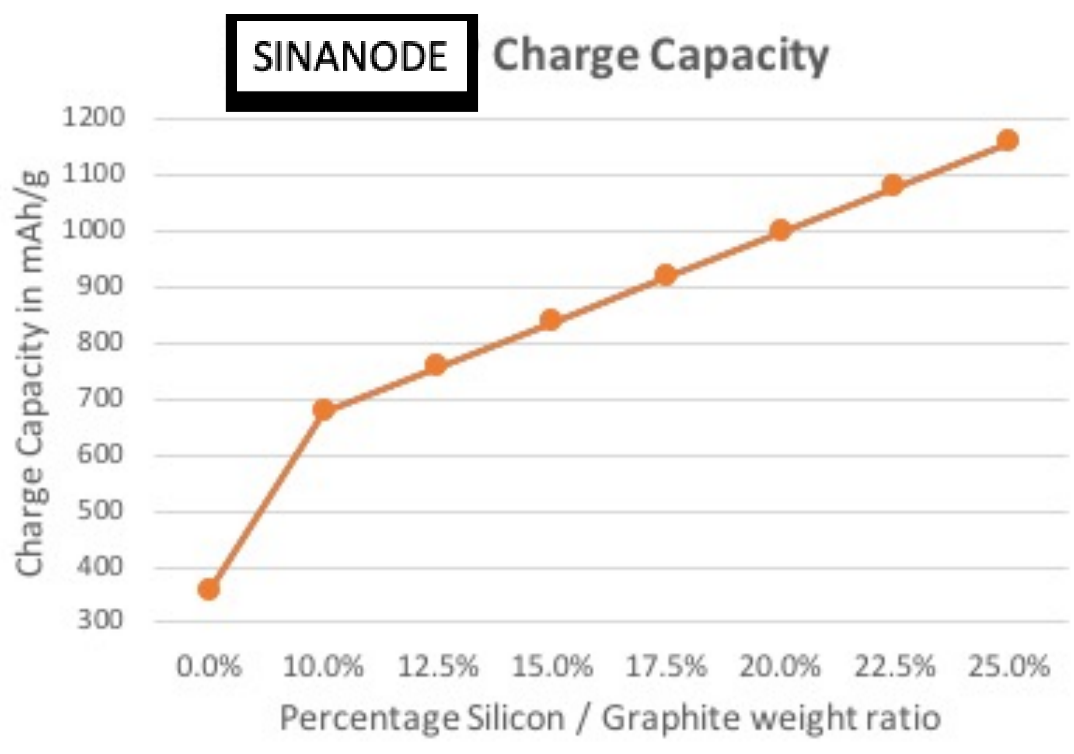
Originally, SINANODE® materials were produced using gold-catalyzed graphite in small CVD reactors. Today SINANODE® materials are produced using copper-catalyzed graphite in much larger CVD reactors which are capable to annually produce from 100 to 1000 tons of SINANODE® materials per plant, depending on the dimension and numbers of the furnace stacks operating in parallel. The transition from the initial gold-catalyzed small-scale production process to the new copper-catalyzed industrial-scale qualified process is the result of over a decade of R&D activities carried over by OneD's CTO Dr. Yimin Zhu and his team.

The benefits achieved by transitioning from the initial gold-catalyzed small-scale process to the copper-catalyzed industrial-scale process are substantial and include the following:

- The synthesis and deposition of copper catalyst is significantly less expensive than the gold catalyst deposition.
- The VSS process enables a higher density of silicon nanowires on the underlying commercial graphite substrate, thus a higher energy density of SINANODE® anodes as a result of Si to C ratios ranging from 10% to 30%.
- The larger industrial-scale CVD reactors in use today enable to scale-up SINANODE® production to an annual production rate per plant ranging from 100 to 1000 tons of SINANODE® at a very competitive cost.

Today's production process is already fully qualified to produce and sell SINANODE® materials with silicon to carbon weight percentage equal to 10%. This corresponds to a charge capacity of about 678 mAh/g for SINANODE® materials based on graphite substrate having charge capacity of about 357 mAh/g. In other words, the addition of 10% silicon content almost doubles the charge capacity of the graphite active material.

The OneD team has already produced SINANODE® materials with higher silicon content. For example, using the same commercially available graphite, SINANODE® active materials have been produced in pilot production at silicon to carbon weight percentage equal to 15%, 20% and even higher percentages, with increasing charge as illustrated by the graph on the right.



2. Specific Capacity of SINANODE® materials and ICE of SINANODE® anodes

The charge capacity of SINANODE® materials is a function of the charge capacity of the graphite "Cap_g" and the weight percentage of silicon content "Si%". Using as a reference Cap_g = 357 mAh/g, the charge capacity of the SiNANOde® active material can be estimated as follow:

$$Capacity_{(Si\%)SINANODE^{®}} = [\ (1 - Si\%) \cdot 357 + Si\% \cdot 3{,}570\ ]\ mAh/g$$

The initial columbic efficiency ("ICE") of SINANODE® anodes typically ranges between 91% and 94%, depending on the underlying graphite substrate. Thus, with Si% = 10%, a SINANODE® anode achieves a reversible capacity which is greater than 600 mAh/g; with Si% = 20%, a SINANODE® anode can achieves a reversible capacity approaching 1000 mAh/g, when paired with NCA or NMC cathodes in a full electrochemical cell.

The SINANODE® powder can be used "as is", i.e. as ready-to-use active material, and mixed with binder and conductive additive in a slurry (see below). In addition, the SINANODE® powder can be "diluted" by mixing it with the same graphite used as the underlying substrate to grow the nanowires. For example, 20% SINANODE® can be mixed 1:1 with graphite to achieve a blend of 10% Si content or can be mixed at any other ratio to meet a customer's specific needs.

For example, a 1:4 dilution of 20% SINANODE® with graphite leads to 4% Si to graphite ratio in the anode active material, and with traditional cell design, including electrolytes without FEC additive, a long cycle life comparable to that achieved with a graphite-only anode can be realized (e.g. 1000+ cycles at 80% retention even at higher C rates), but with the extra energy density provided by the silicon nanowires, as calculated with the equation provided above.

3. Electrode Coating:

With SINANODE® materials, the slurry preparation can use traditional shearing/propelling and planetary mixing with water-based CMC and a solid content within the 25 to 40% range.

The suggested electrode density for most applications is within the 1.1 to 1.5 g/cm^3 and the electrode loading between 2 and 5 mAh/cm^2 upon cathode matching.

Binders suitable to use in water-based slurries include CMC, CMC-SBR, PAA. Binders suitable for us in NMP-based slurries include PAN, PAA, PVDF and its combination. Various conductive carbon can be used such as: Super P, Ketjen black, LITX-G300 graphene powder, LITX200 carbon and CNTs.

4. Matching with various cathodes:

Both OneD and battery makers have successfully matched SINANODE® anodes with various cathodes: NCA, NMC811, NMC622, NMC532, NMC111, LCO, LFP and blended cathodes.

5. Formation:

With SINANODE® materials, there is no need to pre-lithiate the anode. A typical formation protocol of a few cycles at C/20 or C/30 is sufficient to form a stable SEI and condition the cells for normal cycling.

6. Examples of cell performance:

For evaluation purposes, OneD Material can provide coated electrodes or dry pouch cells or SINANODE® powder.

For example, NCA pouch cells have been used to evaluate the various Si% SINANODE® anodes exhibiting an ICE > 90%; >600 cycles at 80% retention (100% DoD) using C/3 charge and C/2 discharge, with the reversible charge capacities indicated earlier in this memo.

For cells using blended SINANODE® – Graphite anodes with 400mAh/g of reversible specific capacity and 4.5% CMC-SBR binder, the ICE is at least 90% (matched to a NCA cathode) and the cells can be cycled for 1000 cycles at 90% retention using C/3 charge and C/2 discharge. For 450mAh/g of reversible specific capacity in the blended anode (also with CMC-SBR), the cells exhibit an ICE of 90% and can be cycled for 800 cycles at 80% retention using C/3 charge and C/2 discharge.

In collaboration with various battery makers, many types of lithium ion battery formats have been built: from small cylindrical cells (18650 format) to large 60 Ah EV demonstration cells.

More detailed results and samples can be shared under NDA with qualified battery makers and end customers.