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Germanium Tin Alloy Nanowires as Anode Materials for High Performance Li-Ion Batteries

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ABSTRACT: The combination of two active Li-ion materials (Ge and Sn) can result in improved conduction paths and higher capacity retention. Here we report; for the first time; the implementation of $\text{Ge}_{1-x}\text{Sn}_x$ alloy nanowires as anode materials for Li-ion batteries. $\text{Ge}_{1-x}\text{Sn}_x$ alloy nanowires have been successfully grown via vapor-liquid-solid (VLS) technique directly on stainless steel current collectors. $\text{Ge}_{1-x}\text{Sn}_x$ ($x = 0.048$) nanowires were predominantly seeded from the $\text{Au}_{0.80}\text{Ag}_{0.20}$ catalysts with negligible amount of growth was also directly catalysed from stainless steel substrate. The electrochemical performance of the the $\text{Ge}_{1-x}\text{Sn}_x$ nanowires as an anode material for Li-ion batteries was investigated via galvanostatic cycling and detailed analysis of differential capacity plots. The nanowire electrodes demonstrated an exceptional capacity retention of 93.4 % from the 2nd to the 100th charge at a C/5 rate, while maintaining a specific capacity value of ~921 mAh/g after 100 cycles. Voltage profiles and differential capacity plots revealed that the $\text{Ge}_{1-x}\text{Sn}_x$ nanowires behave as an alloying mode anode material, as reduction/oxidation peaks for both Ge and Sn were observed, however it is clear that the reversible lithiation of Ge is responsible for the majority of the charge stored.

Keywords: Nanowire; GeSn alloy; Li-ion battery;

1. Introduction

Advancement in Li-ion batteries requires the availability of scalable, cost-effective materials with high energy density.[1] Despite its relatively low capacity (372 mAh/g), graphite remains to be the most commonly used anode material for Li-ion batteries.[2] Other group IV materials, such as Si, Ge and Sn, exhibit bulk capacities far in excess of those of graphite (3579 mAh/g, 1620 mAh/g, , 991 mAh/g respectively),[3] however, due to the enormous expansion of bulk Ge and Si upon lithiation, leading to the pulverisation of the material, the cycle life, and thus retention of the material, is decreased. Nanowires offer a unique solution to this problem; the ability of nanowires to transition from crystalline to amorphous phase while retaining their structural integrity make them suitable materials for use in Li-ion batteries. Hence, the manufacturing of group IV nanowires for use as battery materials has been widely explored.[3–6] Ge nanowires in particular have been identified for their suitability as anode materials in Li-ion batteries.[2,7–10] Both Sn and Pb-catalysed Ge nanowires have previously been reported to demonstrate high capacities when used as an anode material for Li ion batteries[11], however there are no reports on the effect of the incorporation of Sn in the Ge nanowire lattice on the performance of Li-ion battery.

Ge shows enhanced battery performance over its group IV counterparts, Si and Sn, and increased carrier mobility.[12] However, Ge also demonstrates poor cycling life and capacity fading. With its high electronic conductivities and theoretical capacity, Sn is a good candidate for alloying with Ge for energy storage applications.[13] The combination of two active Li-ion materials can result in improved conduction paths with higher capacity retention[14] due to different level of expansion of Ge and Sn component in the alloy with lithiation.[15] The use of a $\text{Ge}_{1-x}\text{Sn}_x$ alloys has previously been shown to enhance the energy storage properties of

Ge in nanocrystal and amorphous form.[12–14] $\text{Ge}_{1-x}\text{Sn}_x$ nanocrystals with $x = 0.05$ showed an improvement in capacitance and retention over Ge nanocrystals.[12] However, the surface area of these nanomaterials is too high, leading to significant side reactions.[14] The open continuous channel along the axis of a nanowire, on the other hand, could result in an increase in capacity and retention due to a decrease in sidewall reactions.[16] Further to this, relative cost of the Ge anode materials could be also reduced by alloying it with the cheaper and more abundant Sn. Therefore, we report the fabrication of $\text{Ge}_{1-x}\text{Sn}_x$ alloy nanowires using AuAg alloy nanoparticle catalyst, which are grown directly on stainless steel current collector for use as anode materials in Li-ion batteries. The growth of $\text{Ge}_{1-x}\text{Sn}_x$ nanowires directly on the stainless steel current collector eliminates the requirement to prepare a conductive slurry of the active material with a binder. The high capacities ($> 900 \text{ mAh/g}$ after 100 cycles) and impressive capacity retention verify the potential of our binder-free $\text{Ge}_{1-x}\text{Sn}_x$ nanowire electrodes as promising anode materials.

2. Method

Nanowire fabrication process: For the catalyzation of $\text{Ge}_{1-x}\text{Sn}_x$ nanowires in a three phase bottom-up growth dodecanethiol-stabilized, phase pure, $\text{Au}_{0.80}\text{Ag}_{0.20}$ alloy nanoparticles were used. Colloidal nanoparticles were synthesized by co-reducing a mixture of chloroauric acid (HAuCl_4) and silver nitrate (AgNO_3) in a chloroform/water biphasic solution.[22,24,40,41] These metal nanoparticles were deposited on to a stainless steel substrate via spin coating. A metal reaction vessel containing the nanoparticle-coated substrate was then left under vacuum at 180°C for 12 hr to ensure a moisture-free growth atmosphere and the desorption of the surfactant molecules from the nanoparticle catalysts.

The Ge and Sn sources used were diphenylgermane (DPG) and tetraethyltin (TET) respectively. These precursors were dissolved in anhydrous toluene (10 ml) in an N₂ filled glove box with typical Ge and Sn precursor volumes of 0.025 ml and 0.0045 ml respectively. A solution containing both Ge and Sn precursors was loaded into a Hamilton sample-lock syringe inside the nitrogen-filled glovebox.

Au_{0.80}Ag_{0.20}-coated stainless steel substrate was further annealed for 15 min at 440 °C under a flowing H₂/Ar atmosphere inside a tube furnace prior to the injection of precursors. The precursor solution was then injected into the metal reaction vessel using a syringe pump at a rate of 0.025 ml min⁻¹. A H₂/Ar flow rate of 0.6 sccm was maintained during the entire growth period. Various growth times were employed to determine the growth rate, ranging from 15 – 120 min.

Characterization of nanowires: Bottom-up grown Ge_{1-x}Sn_x nanowires were imaged on a FEI Helios NanoLab 600i scanning electron microscope (SEM). All energy-dispersive X-ray (EDX) measurements were recorded in high-angle annular dark-field mode in the FEI Helios NanoLab 600i operating at 30 kV and 0.69 nA with an attached Oxford X-Max 80 detector. Error in the EDX measurements indicates a standard error of 0.5 at. %. HRTEM imaging was performed in Titan Themis transmission electron microscope.

Characterization of nanowires as anode in Li-ion battery: The electrochemical performance of the nanowires is evaluated on the stainless steel substrate which also functions as a current collector. As they are grown on the stainless steel they are quite well adhered to the substrate. One of the novel aspects of the electrodes is that they do not have to add any additional processing steps, for example preparation of a slurry consisting of our nanowires with a

conductive additive and a binder. Electrochemical measurements were performed using a BioLogic VSP Potentiostat/Galvanostat. The electrochemical properties of $\text{Ge}_{1-x}\text{Sn}_x$ nanowire samples were investigated in a half cell configuration against a pure Li counter electrode in a two electrode, stainless steel split cell (a coin cell assembly that can be disassembled for post-mortem analysis). The electrolyte used consisted of a 1 mol dm^{-3} solution of lithium hexafluorophosphate salt in a 1:1 (v/v) mixture of ethylene carbonate in dimethyl carbonate with 3 wt% vinylene carbonate. The separator used was a glass fiber separator (El-Cell ECC1-01-0012-A/L, 18 mm diameter, 0.65 mm thickness). The mass loading for anode samples was $\sim 0.3 \text{ mg per } 0.5 \text{ cm}^2$ and no additional conductive additives or binders were added. A Mettler Toledo XP2U ultra micro balance was used to determine the mass of $\text{Ge}_{1-x}\text{Sn}_x$ nanowire material on the stainless steel substrates. Galvanostatic cycling was performed at 0.2 C in a potential window of 1.5 – 0.01 V (vs Li/Li⁺).

3. Results & Discussion

The direct growth of $\text{Ge}_{1-x}\text{Sn}_x$ nanostructures on a stainless steel substrate for use as anode material for Li-ion batteries presents a new venture in the growth of $\text{Ge}_{1-x}\text{Sn}_x$ nanowires, and to our knowledge, this study represents the first reported instance of $\text{Ge}_{1-x}\text{Sn}_x$ alloy nanowires for use in Li-ion batteries. Nanowire growth was carried out via a bottom-up method using diphenylgermane (DPG) and tetraethyltin (TET) as the Ge and Sn sources respectively, and $\text{Au}_{0.80}\text{Ag}_{0.20}$ nanoparticles as the growth catalysts.[17] A liquid-injection CVD approach was adapted for the growth of nanowires at 440 °C on stainless steel current collector substrate. A scanning electron microscopy (SEM) image of $\text{Ge}_{1-x}\text{Sn}_x$ nanowires grown on stainless steel is presented in Figure 1(a). The nanowires have a mean diameter of $75 \pm 30 \text{ nm}$. Low resolution STEM imaging (Figure 1(b)) reveals bright contrasted spherical nanoparticles at the tips of the

nanowires and negligible tapering of nanowire along their lengths. Energy dispersive X-ray (EDX) analysis of the $\text{Ge}_{1-x}\text{Sn}_x$ nanowires revealed an average Sn content of 4.8 ± 2.1 at. %. This Sn incorporation was consistent throughout the nanowire body; without considering the spherical tip, both radially and axially, as verified by EDX elemental mapping (Figure 1(c)). EDX mapping also revealed the formation of a Sn-rich alloy at the tips of the nanowires at a growth temperature of 440 °C (Figure 1(c)).

However, the use of a stainless steel substrate did alter the quality of the grown nanowires, in terms of morphology and Sn content, compared to $\text{Ge}_{1-x}\text{Sn}_x$ nanowires previously grown on Si substrates under similar growth constraints [17,18]. These differences could possibly be due to the difference in the surface energies of the Si and stainless steel substrates which result in different wetting and surface curvatures of the intermediate eutectic liquid (AuAg-Sn-Ge in this case) during VLS growth. Differences in the curvature of the liquid eutectic can readily influence the absorption of growth species and growth kinetics at different interfaces (vapor-liquid, liquid-solid *etc.*), thus resulting in $\text{Ge}_{1-x}\text{Sn}_x$ nanowires with different morphologies. Further to this, the incorporation of Sn in Ge is aided by “solute trapping” of Sn impurities which could be influenced by the growth kinetics, interfacial geometry and strain at different interface.[17,18] Thus a different Sn incorporation in the GeSn alloy nanowires is observed for stainless steel substrates compared to Si growth substrate. Additionally, the possible participation of iron-based catalysts as additional growth promoters[19] from the stainless steel substrate may also have resulted in a vapor-solid-solid (VSS)-like nanowire growth regime, thus resulting in wider diameter distribution of nanowire (Supporting Info, Figure S1). The large variation in the Sn content (4.8 ± 2.1 at. %) in the $\text{Ge}_{1-x}\text{Sn}_x$ nanowire sample can be attributed to the two competing growth regimes present with the participation of two different

growth promoters. Analysis of the catalyst seed at the nanowire tips also revealed two distinct compositions, Fe rich Fe/Ge/Sn and Sn rich Au/Ag/Ge/Sn (Figure 1(d) and (e)). The Ge/Fe rich nanowire tips had a composition of approximately 65 at. % Fe and 35 at. % Ge with minimal Sn incorporation (~ 3 at. %). These Fe_2Ge catalysed VSS like growth resulted in Sn deficient (≈ 1 at.%) $\text{Ge}_{1-x}\text{Sn}_x$ nanowires (Figure S2 in Supporting Information). Alternatively, $\text{Ge}_{1-x}\text{Sn}_x$ nanowires with Sn rich tips, containing Au and Ag, contained a higher Sn amount (> 5 at. %). By analysing the nanowire tips (approximately 50 nanowires), it was found that statistically ~ 75 % of the nanowires were seeded by Au/Ag/Sn seed with high Sn. Fe-seeded nanowires accounted for a minority of the $\text{Ge}_{1-x}\text{Sn}_x$ nanowires grown. The lower Sn composition (~ 1 at. %) in the $\text{Ge}_{1-x}\text{Sn}_x$ nanowires (Supporting Info, Figure S2) seeded directly from stainless steel substrate is expected due to the VSS nature of the Fe seeded $\text{Ge}_{1-x}\text{Sn}_x$ growth; the eutectic temperatures of Fe-Ge[20] and Fe-Sn[21] are far above the growth temperature of the $\text{Ge}_{1-x}\text{Sn}_x$ nanowires. As Sn incorporation is likely aided by a solute trapping mechanism,[17,22] participation and formation of a Fe-Ge-Sn based stable alloy solid growth seeds with very low Sn content does not encourage incorporation and trapping of Sn impurities at the seed-nanowire interface. Interestingly, in the Fe-seeded $\text{Ge}_{1-x}\text{Sn}_x$ nanowires, Sn was still present in non-trivial amounts in the majority of the nanowires (Supporting Info, Figure S2). However, as both of these nanowire types; catalysed from stainless steel and AuAg alloy seeds; contribute as anode materials in Li-ion batteries to the overall capacitance and cycle life, both types of $\text{Ge}_{1-x}\text{Sn}_x$ nanowire were included in the determination of the average Sn composition.

High resolution scanning transmission electron microscopy (HRSTEM) of the $\text{Au}_{0.80}\text{Ag}_{0.20}$ -seeded $\text{Ge}_{1-x}\text{Sn}_x$ nanowires ($x = 0.048$) revealed the highly crystalline nature of the nanowires with sharp seed/nanowire interfaces (Figure 2). Figure 2(a) depicts the bright field HRSTEM image of a defect free, single crystalline $\text{Ge}_{1-x}\text{Sn}_x$ nanowires. As defect free materials allow

for a long life cycles, the structural uniformity of the $\text{Ge}_{1-x}\text{Sn}_x$ nanowires is imperative for their use as Li ion anode materials.[23] Fast Fourier Transform (FFT) analysis of the nanowire, with $\langle 110 \rangle$ zone axis alignment (Figure 2(a) inset), revealed an interplanar spacing (d) of 0.33 nm, which is marginally larger than the d value for bulk diamond Ge crystals of 0.326 nm (JCPDS 04–0545). The d spacing is expected to increase upon the incorporation of Sn into the Ge host lattice due to the difference in the lattice constants of Ge and Sn, which can instigate a lattice expansion, and has been previously reported.[22] The nanowires predominantly displayed a $\langle 111 \rangle$ growth direction, the most common growth orientation for Ge nanowires with a mean diameter above 50 nm[22,24]. Generally, the crystal structure of the $\text{Ge}_{1-x}\text{Sn}_x$ alloy nanowires, with various Sn incorporations, exhibited a 3C lattice arrangement without any stacking faults and twin boundaries. The interface between the nanowire seed and body was examined and can be seen in Figure 2(b). No apparent tailing or segregation of Sn from the Sn rich seed was observed, confirming the sharp junction at the interface as indicated from the EDX elemental maps in Figure 1(c). The interplanar spacing of the nanowire seed (d) was 0.28 nm, confirmed by measurement of the lattice spacing for multiple layers. The interplanar spacing and FFT of a nanowire seed (Figure 2(b), inset) matches well with tetragonal Sn (JCPDS 04–0673), confirming the Sn-rich nature of the nanowire seed.

The electrochemical performance of the $\text{Ge}_{1-x}\text{Sn}_x$ nanowires as an anode material for Li-ion batteries was investigated via galvanostatic cycling in a half-cell configuration versus Li metal. A selection of the charge and discharge voltage profiles obtained from galvanostatic cycling using a C/5 rate are shown in Figure 3(a) and (b). The first charge curve consisted of a sloping region from an open circuit voltage (OCV) (3.20 V) to ~ 0.35 V, followed by a long plateau from ~ 0.30 V to the low potential limit of 0.01 V. The sloping region is associated with the formation of a solid-electrolyte interphase (SEI) layer and the irreversible decomposition of

the electrolyte on the surface of the $\text{Ge}_{1-x}\text{Sn}_x$ nanowires.[25] The plateau is attributed to the alloying of the nanowires with Li.[26] The first discharge curve consisted of a plateau at ~ 0.50 V, corresponding to the dealloying of the $\text{Ge}_{1-x}\text{Sn}_x$ nanowires. The initial charge and discharge capacities were ~ 1716 and 867 mAh/g, respectively, corresponding to an initial Coulombic efficiency (ICE) of 50.5% . The large initial charge capacity is likely due to the formation of an SEI layer on the surface of the nanowires as well as the formation of quasi reversible Li_2O .[27] The ICE value obtained for $\text{Ge}_{1-x}\text{Sn}_x$ nanowires is comparable to or greater than ICE values reported for other Ge nanowire anodes.[7,28] Low ICE is a persistent issue for alloying mode anode materials such as Ge and Si based negative electrode materials however, there are some reports demonstrating that the prelithiation of Si nanostructures can improve ICE values. Forney et al. prelithiated Si-CNT anodes via mechanical pressing of stabilized lithium metal powder onto the working electrode, and demonstrated a significant increase in ICE values.[29] The voltage profiles from the 2nd cycle to the 100th cycle are quite consistent, which is indicative of a highly reversible process.

$\text{Ge}_{1-x}\text{Sn}_x$ nanowires have potential to demonstrate stable capacity retention due to lower volume expansion (305%) of Sn compared to Ge (382%).[15] The specific capacity values obtained over 100 cycles at a rate of C/5 and the corresponding coulombic efficiencies are shown in Figure 3(c). The specific capacity after the 2nd charge was ~ 986 mAh/g and after 100 cycles this decreased marginally to ~ 921 mAh/g, corresponding to an exceptional capacity retention of 93.4% . The average Coulombic efficiency from the 2nd to the 100th cycle was also impressive, having a value of 97.8% . Preserving such a high level of capacity after 100 cycles clearly validates the viability of $\text{Ge}_{1-x}\text{Sn}_x$ nanowires for use as an anode material in practical commercial Li-ion cells. The specific capacity values achieved for the $\text{Ge}_{1-x}\text{Sn}_x$ nanowires are comparable to [11,30] or greater than [31–34] previously reported values for other Ge based

anode materials. Notably, the impressive electrochemical performance of the GeSn nanowires was achieved without the need of conductive additives or binders.

In order to better appreciate the charge storage mechanism of the $\text{Ge}_{1-x}\text{Sn}_x$ nanowires, which results in their impressive capacity retention properties, differential capacity plots from galvanostatic charge and discharge curves were calculated. The initial charge curve consisted of a series of plateaus which can be seen more clearly in the differential capacity plot (DCP) presented in Figure S3(a). The DCP for the first charge consisted of 5 peaks in total. The wide band centred at ~ 1.21 V is associated with the formation of an SEI layer and is only observed during the first cycle.[35] The weak peak present at ~ 0.74 V may be attributed to the alloying of Li with the low amount of Sn (4.8 at. % Sn) which is present in the nanowires. A reduction peak at this potential has previously been reported for Sn-based anode materials.[30] The strong, sharp peak centred at 0.35 V is due to the lithiation of crystalline Ge (c-Ge) and is only observed during the first cycle, suggesting that after the initial lithiation of the nanowires, they do not return to a fully delithiated crystalline Ge phase. A similar observation for this reduction peak was made by Mullane et al. for Cu-catalysed Ge nanowires.[2] The strong peak at 0.19 V and the weaker shoulder at 0.15 V are due to the initial formation of Li-Ge alloys in the form of a- $\text{Li}_{15}\text{Ge}_4$ and c- $\text{Li}_{15}\text{Ge}_4$, respectively.[30] A strong, wide, asymmetric oxidation peak was observed in the first cathodic scan from 0.35 to 0.55 V, which can be deconvoluted into two distinct peaks centred at 0.49 and 0.51 V, as shown in Figure S3(c), corresponding to the delithiation of the c- $\text{Li}_{15}\text{Ge}_4$ and a- $\text{Li}_{15}\text{Ge}_4$ phases, respectively.[36,37]

The DCP for the 2nd charge consisted of two wide peaks centred at 0.53 and 0.39 V and a sharp peak at 0.18 V (Figure S3(d)). The two broad peaks are associated with the formation of

amorphous Li-Ge alloys ($a\text{-Li}_x\text{Ge} \rightarrow a\text{-Li}_{15}\text{Ge}_4$) and the sharp peak is due to the formation of $c\text{-Li}_{15}\text{Ge}_4$. [10,38] Contour plots, calculated from a series of DCPs from charge and discharge voltage profiles, ranging from the 2nd to the 100th cycle are shown in Figure 4. The reduction peaks associated with the formation of the $a\text{-Li}_{15}\text{Ge}_4$ and $c\text{-Li}_{15}\text{Ge}_4$ phases, centred at 0.39 and 0.18 V, remain present during the 100 cycles, as shown in Figure 4a. This indicates highly reversible lithiation/delithiation of $\text{Ge}_{1-x}\text{Sn}_x$ nanowires. The presence of these reduction peaks and the consistency of the potentials at which they occur is a major contributing factor to the impressive capacity retention of the nanowires from the 2nd cycle onwards. Initially the majority of the charge stored by the $\text{Ge}_{1-x}\text{Sn}_x$ nanowires is due to the formation of the $c\text{-Li}_{15}\text{Ge}_4$ phase, as indicated by the red area in Figure 4a, however as cycling continues the intensity of this reduction peak decreases slightly while the intensity of the reduction peak associated with the formation of the $a\text{-Li}_{15}\text{Ge}_4$ phase remains consistent. This suggests that with increased cycling more of the charge stored is due to the transition from $a\text{-Li}_x\text{Ge} \rightarrow a\text{-Li}_{15}\text{Ge}_4$.

The contour plot calculated from the DCPs for discharge curves is shown in Figure 4d. The asymmetric oxidation peak associated with the delithiation of the $c\text{-Li}_{15}\text{Ge}_4$ and $a\text{-Li}_{15}\text{Ge}_4$ phases remains after 100 cycles, however there is a significant decrease in the intensity after the first 30 cycles. The stacked DCPs in Figures 4e and f indicate that the width of the peak increases with increased cycling, which may be associated with decreased charge storage due to the formation of the $c\text{-Li}_{15}\text{Ge}_4$ phase. Of note, the discharge capacity values presented in Figure 4c do not significantly decrease after 30 cycles, hence the widening of this oxidation peak with increased cycling does not have a substantial negative influence on the overall charge stored. Initially the majority charge storage mechanism for the $\text{Ge}_{1-x}\text{Sn}_x$ nanowires is the formation of the $c\text{-Li}_{15}\text{Ge}_4$ phase, however as cycling continues, less charge is being stored via the formation of this phase and more of the overall charge stored is due to the formation of the

a-Li₁₅Ge₄ phase. We have previously observed a similar trend for GeO₂ inverse opal structured anodes, whereby after a number of cycles the preferred charge storage mechanism was the formation of the a-Li₁₅Ge₄ phase rather than the c-Li₁₅Ge₄ phase.[39] Deformation and electrochemical restructuring of nanowire morphology and amorphization of the GeSn material; similar to Ge nanowires [30]; was observed after 100 cycles (Figure S4 in Supporting Information). Formation of a mesh of active material by agglomeration of individual nanowires was observed for phase pure Ge nanowire after 100 cycles. [30] A very similar behavior was observed for the GeSn nanowires where a porous network of active material with ligament and mesh like morphology is formed after 100 cycles. Actually, compared to the phase pure Ge nanowire these GeSn nanowire shows better retention of nanowire morphology with the withholding of the cylindrical shape after 100 cycles (Figure S4), though other factors such as dimension, cycling rate, anode fabrication method etc. may affect this transformation. Retention of the alloy structure is also confirmed from the corresponding EDX mapping (Figure S4) with no apparent sign of phase segregation of Ge or Sn in the cycled structure.

4. CONCLUSION

Ge_{1-x}Sn_x alloy nanowires were successfully grown directly on stainless steel substrates, current collectors for Li-ion battery, thus eliminating the requirement to prepare a conductive slurry of the active material with a binder. Ge_{1-x}Sn_x nanowires with $x \approx 0.048$ were determined to be seeded both from the Au_{0.80}Ag_{0.20} nanoparticle catalyst and from the substrate itself (Fe). The Ge_{1-x}Sn_x nanowires were single crystalline and defect free prior to lithiation. The electrochemical performance of the the Ge_{1-x}Sn_x nanowires as an anode material for Li-ion batteries was investigated via galvanostatic cycling. The nanowire electrodes demonstrated an exceptional capacity retention of 93.4 % from the 2nd to the 100th charge at a C/5 rate, while

maintaining a specific capacity value of ~921 mAh/g after 100 cycles. Voltage profiles and differential capacity plots revealed that the $\text{Ge}_{1-x}\text{Sn}_x$ nanowires behaved as a dual alloying mode anode material as reduction/oxidation peaks for both Ge and Sn were observed. However, it was clear that the reversible lithiation of Ge was responsible for the majority of the charge stored due to the relatively low amount of Sn present within the alloy nanowires (4.8 at. % Sn). A future goal would be to find the Sn based group IV binary and ternary (including Si) alloy nanomaterials with critical composition as the highly efficient anode material for Li-ion battery.

Supporting Information

The Supporting Information is available from IOP.

Supporting Information content experimental method, diameter distribution, EDX spectra and differential charge curves and STEM images of cycled material.

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Conflict of Interest

The authors declare no competing financial interest.

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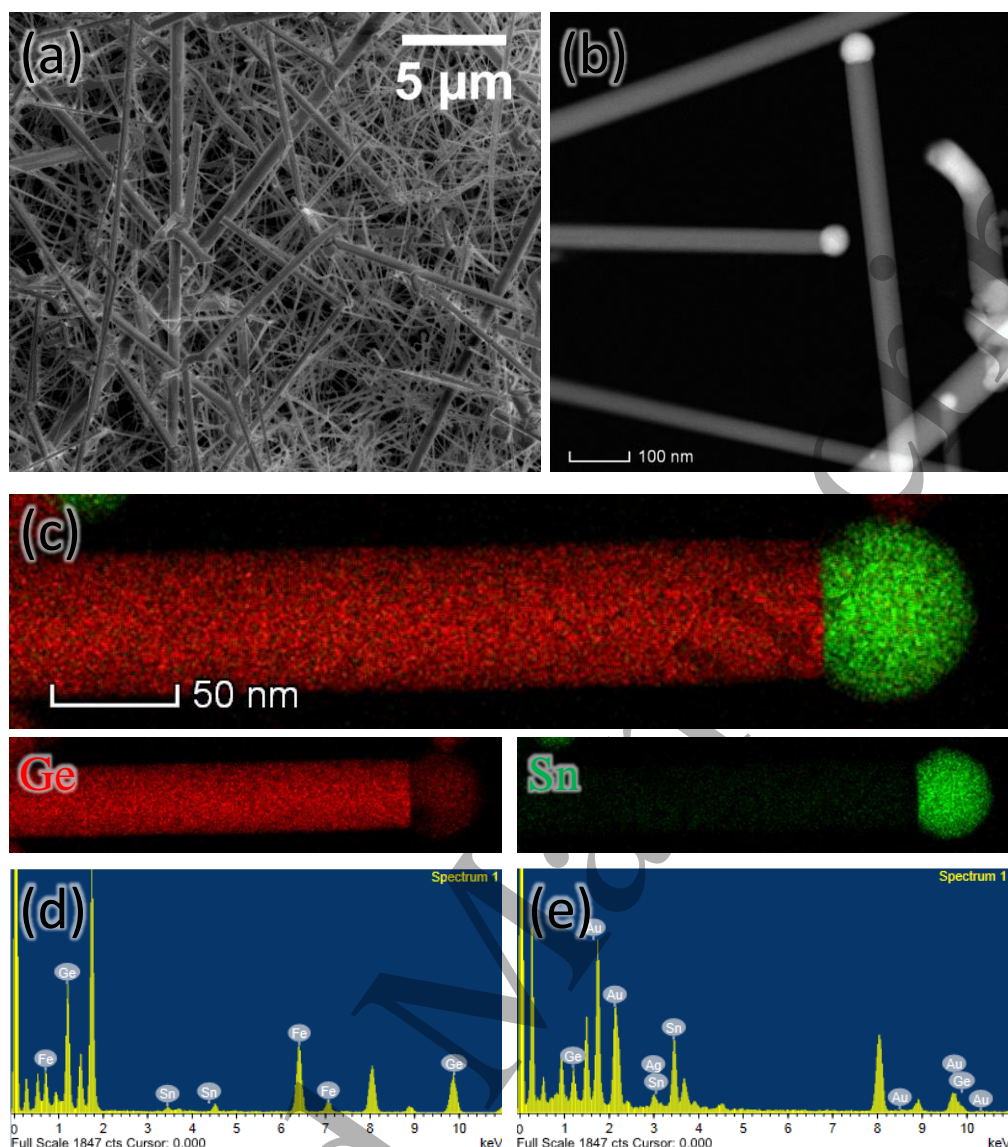


Figure 1: Structural and compositional analysis of $\text{Ge}_{1-x}\text{Sn}_x$ nanowires. SEM and STEM images of the $\text{Ge}_{1-x}\text{Sn}_x$ nanowires grown on stainless steel reveal a large variation in nanowire diameter (a) across the substrate, but a negligible change in diameter due to tapering of single nanowires (b) respectively. (c) EDX elemental mapping of $\text{Ge}_{1-x}\text{Sn}_x$ nanowires with $x = 0.048$. Ge is denoted in red and Sn in green. The nanowire in (c) is AuAg-seeded, clearly apparent from the presence of a Sn rich nanowire seed in the elemental map and therefore may have a higher than average Sn content ($x > 0.048$). Evidence of the two competing growth seeds is provided in (d) and (e), with EDX spectra displaying the presence of Fe, and Au and Ag respectively.

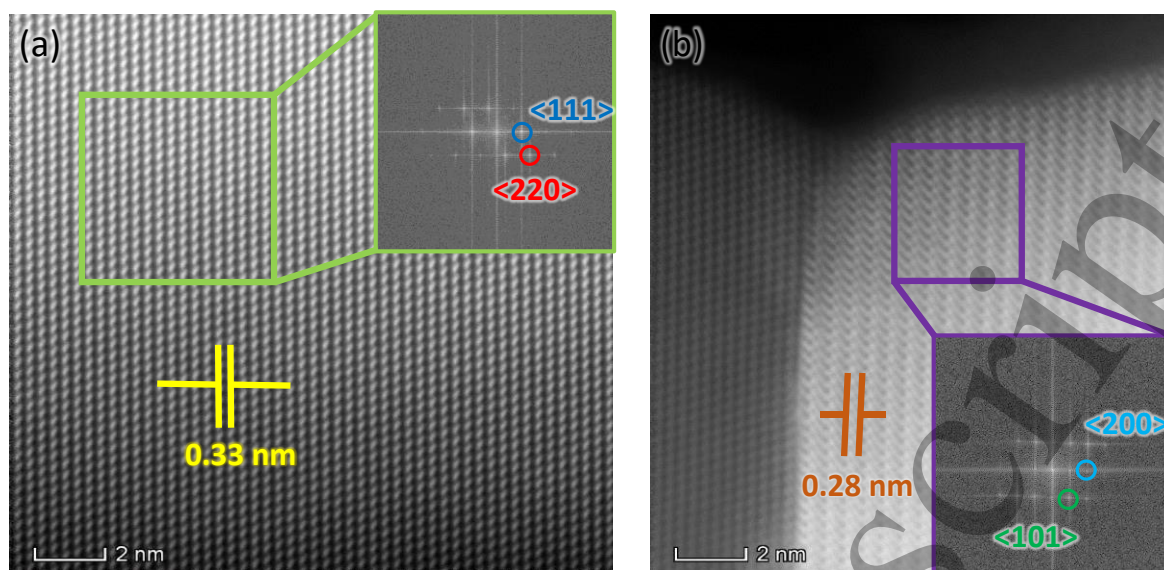


Figure 2: HAADF HRSTEM analysis of $\text{Ge}_{1-x}\text{Sn}_x$ nanowires. (a) The $\text{Ge}_{1-x}\text{Sn}_x$ nanowires are single crystalline with no apparent defects or twin boundaries. The lattice spacing of the nanowires is 0.33 nm, confirmed by FFT (inset). These nanowires are grown along the $\langle 111 \rangle$ direction. The sharp interface between the nanowire seed and body is shown in (b); FFT provided in the inset. There is negligible apparent tailing of the Sn rich seed at the growth interface.

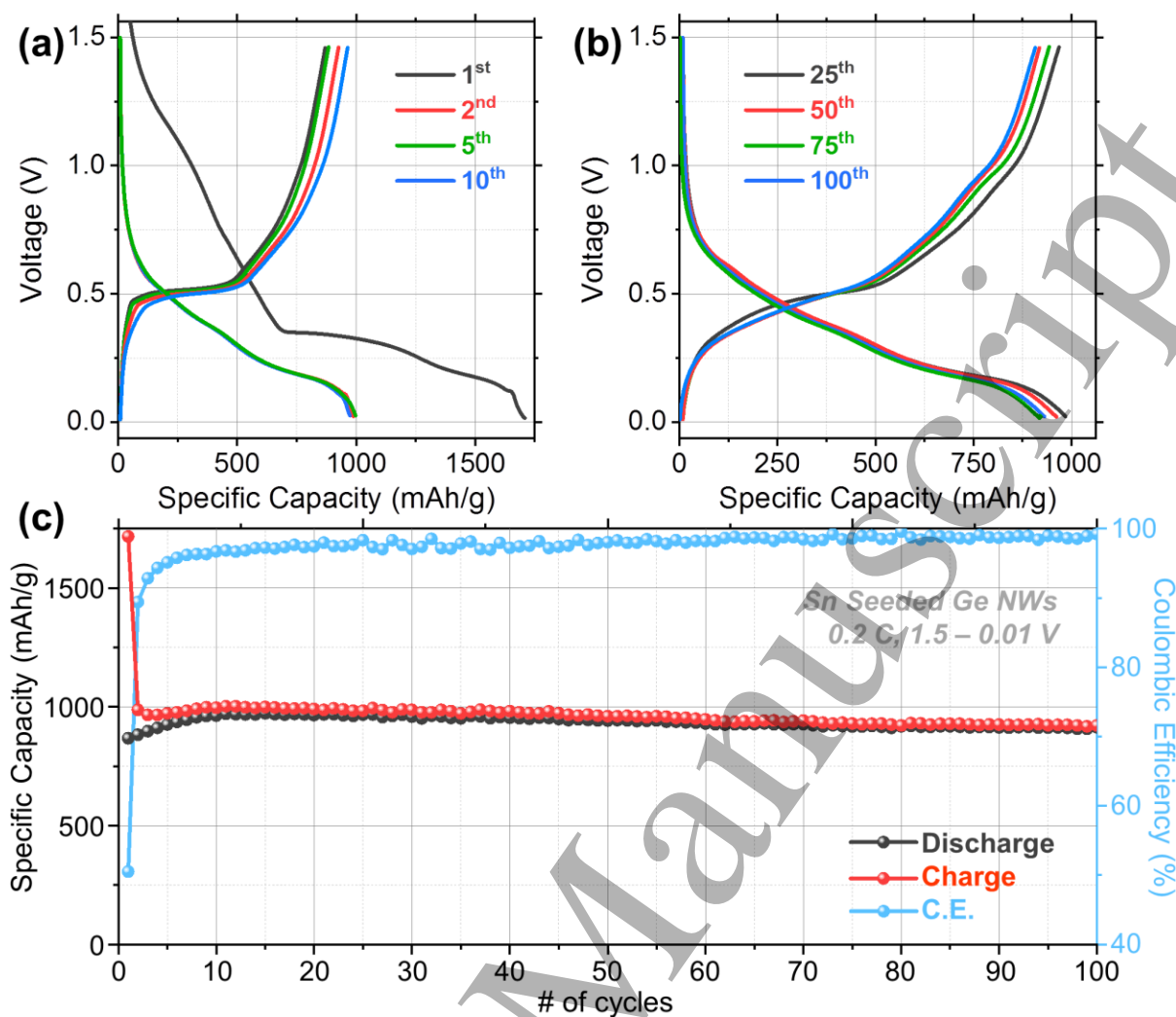


Figure 3: Electrochemical tests. Charge and discharge voltage profiles for (a) the 1st, 2nd, 5th and 10th cycles (b) the 25th, 50th, 75th and 100th cycles for $\text{Ge}_{1-x}\text{Sn}_x$ nanowires at C/5 in a potential window of 1.5 – 0.01 V (vs Li/Li+). (c) Specific capacity and Coulombic efficiency values obtained for $\text{Ge}_{1-x}\text{Sn}_x$ nanowires over 100 cycles.

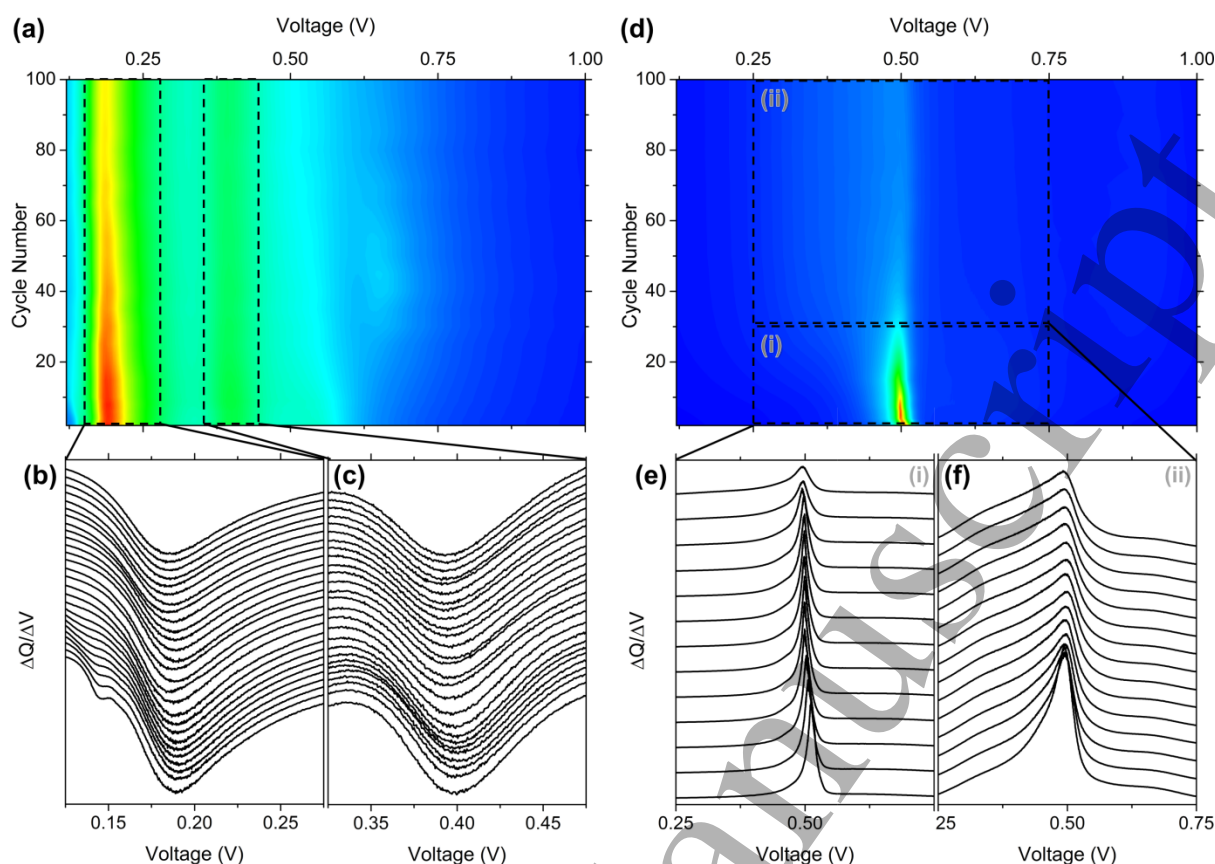


Figure 4: Differential capacity plots. (a) Differential capacity contour plot calculated from differential charge curves. Stacked differential capacity curves demonstrating the reduction peak associated with the formation of (b) the c-Li₁₅Ge₄ phase and (c) the a-Li₁₅Ge₄ phase. (d) Differential capacity contour plot calculated from differential discharge curves. Stacked differential capacity curves demonstrating the oxidation peak associated with the delithiation of for Ge_{1-x}Sn_x nanowires (e) from the 1st to the 30th cycle and (f) from the 31th to the 100th cycle.