Efficient mechanical energy harvesters enable various wearable devices and auxiliary energy supply. Here we report a novel class of mechanical energy harvesters via stress-voltage coupling in electrochemically alloyed electrodes. The device consists of two identical Li-alloyed Si as electrodes, separated by electrolyte-soaked polymer membranes. Bending-induced asymmetric stresses generate chemical potential difference, driving lithium ion flux from the compressed to the tensed electrode to generate electrical current. Removing the bending reverses ion flux and electrical current. Our thermodynamic analysis reveals that the ideal energy-harvesting efficiency of this device is dictated by the Poisson's ratio of the electrodes. For the thin-film-based energy harvester used in this study, the device has achieved a generating capacity of 15%. The device demonstrates a practical use of stress-composition-voltage coupling in electrochemically active alloys to harvest low-grade mechanical energies from various low-frequency motions, such as everyday human activities.
Efficent energy-harvesting devices, which convert energies otherwise wasted to electricity, help decentralize power generation and reduce the distance of electricity transmission. During the last decade, enormous efforts have been dedicated to the development of a variety of energy harvesters, capable of harvesting energy of various forms\textsuperscript{1-3}. In mechanical energy harvesting alone, several types of energy generators have been demonstrated, such as piezoelectric\textsuperscript{4,5}, electrokinetic\textsuperscript{6-9} or triboelectric generators\textsuperscript{10}, and enabled a wide range of applications\textsuperscript{11-16}. Advances in processing techniques such as virus-directed designs\textsuperscript{17} or block copolymer self-assembly\textsuperscript{18} have also been reported. However, these energy generators are most efficient for vibrational energy harvesting at a relatively high frequency (< 20–100 Hz), and inherently limited in the low-frequency regime (0.5–5 Hz) where everyday human activities such as walking take place.

Herein we report a new type of mechanical energy harvester operative in the low-frequency regime. The device uses the stress-composition coupling in electrochemically active materials, such as partially Li-alloyed Si or Ge (refs 19–21). The coupling between mechanical stress and lithiation thermodynamics and kinetics\textsuperscript{22} has been widely recognized in high-capacity anodes of lithium-ion \textit{Li}\textsuperscript{+} batteries, but was usually regarded as an adverse effect\textsuperscript{19,23,24}. Here we demonstrate that mechanical bending induces different stress states in two identical partially Li-alloyed Si electrodes, which drives Li\textsuperscript{+} migration and generates electricity. The prototype generator demonstrates power density of 0.48 \(\mu\)W cm\(^{-2}\) at 0.3 Hz. Our thermodynamic and mechanics analyses lay a theoretical foundation for the device design and optimization.

**Results**

**Working principle and device design.** Figure 1 illustrates the working principle of the energy harvester, consisting of two partially Li-alloyed electrodes sandwiching an electrolyte. In the initial stress-free condition, the two electrodes are isopotential (point A in Fig. 1a and I in Fig. 1b). Bending the device generates net tension in one electrode and compression in the other (points B and C in Fig. 1a and II in Fig. 1b). The asymmetric stress creates a chemical potential difference that drives Li\textsuperscript{+} ion migration from the compressed to the tensed electrode through the electrolyte (see Supplementary Note 1 for the analysis). At the same time, to maintain charge neutrality, electrons flow in the outer circuit, also from the compressive to the tensile sides, generating electrical power. The Li\textsuperscript{+} migration continues until the potential difference vanishes (points B’ and C’ in Fig. 1a and III in Fig. 1b), establishing new equilibrium states on the two electrodes with different Li concentration. When the external stresses are removed by unbending the device, the chemical potential shifts on the electrodes (from point B’ to point B” and from point C’ to point C” in Fig. 1a and III–IV in Fig. 1b). The difference in lithium concentration between the electrodes drives Li\textsuperscript{+} ion migration in the opposite direction (from point B” to point C” to A in Fig. 1a and IV–I in Fig. 1b), thus discharging the device. The device goes back to its original equilibrium state and may go through this cycle multiple times provided that it operates in the viscoelastic regime without any irreversible damage. The electrical energy generated is equivalent to the potential difference multiplied by the amount of Li\textsuperscript{+} migrated, as illustrated as red-colored area in Fig. 1a.

Guided by this vision, we developed a prototype generator, consisting of two identical electrodes sandwiching a separator soaked with electrolyte. We used amorphous \textit{Li}\textsubscript{x}Si (\(x \sim 3.1\)) thin film as the electrodes for its mechanical flexibility and reasonable lithiation and delithiation rates\textsuperscript{25}. Ethylene carbonate mixed with ethyl methyl carbonate, LiPF\(_6\) and micro-porous polypropylene monolayer\textsuperscript{26} were used as the electrolyte, lithium salt and separator, respectively. We selected polyimide as the substrate to which the electrodes attach and Ag current collectors for their strong adhesion and stretchability\textsuperscript{27}. The polyimide substrates were encapsulated by castable rubber, such as polydimethylsilane (PDMS) or polycurethane. Figure 2 shows the schematics of the device and the atomistic view of the active region. Each \textit{Li}\textsubscript{x}Si electrode is 249 nm thick, about two orders of magnitude thinner than the separator layer (25 \(\mu\)m). The thin-film configuration of the device allows large-curvature bending. On bending, the top, compressed electrode becomes an anode, while the bottom, tensed electrode a cathode. The device functions as an energy harvester, and because stress-driven Li\textsuperscript{+} ion diffusion conforms to the Onsager linear-response behaviour, it is expected to exhibit a decent efficiency even with miniscule loads (that is, no threshold behaviour), converting mechanical energy input into electrical energy output.

**Mechanics analysis of the device.** Mechanics analysis provides insight into the energy conversion efficiency. Figure 1b illustrates the bending geometry. Bending the thin-film device generates compressive and tensile strains of equal magnitude (\(\varepsilon_{xx} = \pm h/R\)) on the top and bottom electrodes, respectively, where \(R\) is the radius of curvature and \(h\) the half thickness of the thin-film device. The stress state is obtained under the assumption of elastic deformation. Assuming a plane-stress condition along the \(y\) direction (see Fig. 1b for the coordinates), the stress on the bottom electrode can be written as follows,

\[
\sigma_{xx} = \frac{E h}{(1 - v^2)} \frac{h}{R}, \quad \sigma_{zz} = \frac{v E h}{(1 - v^2)} \frac{h}{R}, \quad \sigma_{yy} = 0, \quad (1)
\]
where \( E \) is the Young's modulus and \( \nu \) the Poisson's ratio. The chemical potential difference between the two electrodes is only related to the difference in the hydrostatic stress \( \sigma_{\text{hydro}} \equiv T \varepsilon \rho(\sigma)/3 \)

\[
\Delta \mu = \Omega_{\text{Li}} \left( \frac{E}{1 - \nu} \right) \frac{2h}{3R}
\]

(2)

Where \( \Omega_{\text{Li}} = 14.95 \text{ Å}^3 \) is the estimated partial molar volume of Li in Li,Si (refs 28,29). This gives a pressure sensitivity of 93 mV per GPa, close to a recent experimental measurement of 110 mV per GPa (ref. 24).

It is noted that the deviatoric part of the stress tensor \( \sigma_{\text{deviatoric}} = \sigma - \sigma_{\text{hydro}} I \) does not couple to the chemical potential, where \( I \) is the identity tensor. Instead, the deviatoric stress \( \sigma_{\text{deviatoric}} \) induces shear deformation which is volume conservative, thus does not generate electrical energy. The total strain-energy \( U_{\text{strain}} \) can be decoupled into the hydrostatic part and the deviatoric part, as:

\[
U_{\text{strain}} = \frac{E}{2(1 - \nu^2)} \left( \frac{h}{R} \right)^2 = U_{\text{hydro}} + U_{\text{deviatoric}},
\]

(3)

with

\[
U_{\text{hydro}} = \frac{\sigma_{\text{hydro}}^2}{2B}, \quad B = \frac{E}{3(1 - 2\nu)},
\]

where \( B \) is the bulk modulus. Only the hydrostatic component \( U_{\text{hydro}} \) can be used for electricity generation, which also varies on lithium insertion and extraction. Assuming all of \( U_{\text{hydro}} \) can be used for electricity generation, while all of \( U_{\text{deviatoric}} \) is wasted, an ideal efficiency can be expressed as

\[
\eta \equiv \frac{U_{\text{electrical}}}{U_{\text{strain}}} = \frac{U_{\text{hydro}}}{U_{\text{strain}}} = \frac{(1 - 2\nu)(1 + \nu)}{3(1 - \nu)}.
\]

(4)

For \( \nu = 0.25 \) (ref. 30), an idealized efficiency of 27.8% is obtained. Interestingly, the energy conversion efficiency is independent of the Young's modulus, and maximizes at \( \nu = 0 \). The total amount of lithium that is expected to transport across the electrolyte to completely relax \( \sigma_{\text{hydro}} \) is

\[
\Delta N_{\text{Li}} = \frac{V_{\text{one side}} T \varepsilon \rho(\sigma)}{3B} = \frac{V_{\text{one side}}}{\Omega_{\text{Li}}} \left( \frac{1 - 2\nu}{1 - \nu} \right) \left( \frac{h}{R} \right).
\]

(5)

where \( V_{\text{one side}} \) is the volume of one Li,Si electrode affected by the radius of curvature and \( V_{\text{one side}}/\Omega_{\text{Li}} \) the amount of Li present in the affected volume determined by previous reports25. It is noted that a thicker electrode increases the amount of migrating lithium and hence the capacity, however, it may also increase the probability for developing structural inhomogeneities such as cracks during lithiation or bending.

**Electrical energy output of the device**. Just like photovoltaic energy harvesters, one could characterize a mechanical energy harvester by open-circuit voltage or short-circuit current. Figure 3a shows the open-circuit voltage, obtained by bending the device in the same direction for 30 s and resting the device for another 30 s with bending force released. The applied radius of curvature was \( R \) cm, corresponding to a maximum tensile stress of 0.018 GPa generated in the electrodes. Since the yield stress of amorphous Li,Si is \( R \) GPa, the material deforms within its elastic regime31. We note that there exists a background potential (nonzero rest potential), which might be due to the side reactions such as a solid electrolyte interface layer formation or any unintentional inhomogeneity in composition between the two electrodes. The open-circuit voltage increases on bending and recovers its resting potential once the bending force is released. This trend is consistent with the relationship between the chemical potential difference and the applied radius of curvature \( (\Delta \mu \sim R^{-1}) \), shown in equation (2). We used experimentally measured value of Young's modulus (25 GPa) for lithiated amorphous silicon thin film, interpolated with rule of mixture for the specific composition we used32. Table 1 shows the predicted hydrostatic stress, voltage and measured voltage values at six different radii of curvature. The measured open-circuit voltages agree well with the predicted values.

Figure 4 shows the measured short-circuit current as the device is bent with a radius of curvature of 0.2 cm and then relaxed by releasing the bending forces. The bending and relaxation periods were 10 s each. Bending induces a sharp rise in the current, suggesting the stress-driven Li\(^+\) migration inside. When holding the bending at a fixed radius of curvature, the current signal quickly reaches a maximum beyond which it decays gradually. This decay is due to the cancellation between the externally applied bending stress and Li insertion/extraction-induced stress in the electrodes. Specifically, externally applied bending creates tensile stress on one electrode and compressive on the other, generating a chemical potential difference that drives Li\(^+\) diffusion across the electrodes. Just like photovoltaic energy harvesters, one could characterize a mechanical energy harvester by open-circuit voltage or short-circuit current. The current signal vanishes when the chemical potential between the two contacting electrodes vanishes. The full
width at half maximum (time for peak current value to drop to half) was 3.0 s on average, which is two orders of magnitude greater than a typical piezoelectric device in similar geometry, promising the applicability of the device in the low-frequency regime.35

On releasing the device from external bending force, Li insertion/extraction-generated stress difference along with the Li concentration gradient in the electrodes serves as the driving force for the backward Li\(^+\) migration, corresponding to a sharp current increase in the opposite direction. As Li\(^+\) migration continues, the stress and concentration difference between the two electrodes drop, so as the driving force for Li\(^+\) diffusion, leading to a reduced current signal. The current signal vanishes when the two electrodes recover to their original, isopotential state. We also performed measurements by alternating the bending directions and the results were consistent with the trends described above, as illustrated in Supplementary Note 2.

The amount of Li\(^+\) ions that migrate during each bending cycle is equivalent to the area under a current peak. In Fig. 4, the area under a peak is ~73 μC. The volume of the affected area during the experiment is estimated to be 1.56 × 10\(^{-5}\) cm\(^3\). (The bending geometry during experiment is shown in Supplementary Note 3.) According to the analysis above, the expected Li\(^+\) ion migration is equivalent to 487 μC. The reversible lithium migration of 73 μC is ~15% of the theoretically predicted amount. The reduced generating capacity per cycle may be caused by ‘self-discharging’, that is, the electrons diffuse out of the bent region to the nearby flat regions within the same Li\(_2\)Si electrode without going to the external circuit, which actually causes the flat regions to curve. Such self-discharging behaviour is predicted to occur whenever there are unequal bending curvatures in the lateral direction (gradient in the bending curvature) and is expected to be a significant cause in low experimentally measured efficiency of the device. (The experimentally measured efficiency is estimated in Supplementary Note 4.) This internal electro-chemical dissipation by self-discharging can be greatly reduced by applying a uniform radius of curvature throughout the device.

**Device durability during repeated bending test.** Figure 5 shows the data from two kinds of repetitive bending fatigue tests. In repeated open-circuit voltage tests, we observe that not only the peak height but also the background voltage are reduced over 1,500 repeated bending cycles. The background current is estimated in Supplementary Note 4.) This internal electro-chemical dissipation by self-discharging can be greatly reduced by applying a uniform radius of curvature throughout the device.

| Radius of curvature (mm) | Hydrostatic stress (GPa) | \(V_{\text{predicted}}\) (mV) | \(V_{\text{measured}}\) (mV) |
|--------------------------|-------------------------|-----------------------------|-------------------------------|
| 13.4                     | 0.010                   | 1.9                         | 1.8                           |
| 9.4                      | 0.015                   | 2.8                         | 2.5                           |
| 5.3                      | 0.026                   | 4.9                         | 5.1                           |
| 4.2                      | 0.033                   | 6.2                         | 5.9                           |
| 2.7                      | 0.051                   | 9.6                         | 8.9                           |
| 1.7                      | 0.081                   | 15.2                        | 22.5                          |
slowly moving towards zero during cycling in a stable manner. Data from repeated bending under different radii of curvature is available in Supplementary Note 5. These results indicate that the electrode materials maintain their homogeneity during cyclic loading of 1,500 cycles. The reliable performance of the device during short-circuit fatigue test is enabled as the migrating lithium ions act as effective stress reliever in the electrode, much the same way as in Nabarro–Herring creep. It might thus be possible to adapt our active mechanical–passive electrochemical fatigue tests as a diagnostic tool to characterize damage creation, repair and accumulation inside electrode materials, as a complementary technique to the electrochemically driven battery cycling testing paradigm that monitors voltage-induced mechanical strain (such as film curvature change).

Since our generator should operate in the elastic regime to minimize damage accumulation, the yield surface of electrode material sets the limit on the voltage output. The atomic volume of lithium is known to be approximately constant in a wide range of lithium alloys independent of lithium content, and thus, an alloy with the greatest yield strength promises the highest voltage output. It is also noteworthy that our device does not cause composition change nearly as large as that in battery electrode reactions, therefore many candidate alloys that do not cycle well as battery electrodes may still be excellent candidates for our generator device. Alloys of larger ions such as sodium or potassium may also be used to provide higher voltage output, as a higher atomic volume promises higher voltage.

**Discussions**

Since the electricity generation is driven by Li+ ion diffusion, the effect of bending rate and frequency can be understood based on the characteristic time scales of Li+ ion diffusion. While there are time scales for mechanical equilibrium and diffusion equilibrium, the mechanical equilibrium in the elastic range is established very fast. Thus, potential bending rate effect comes from the competition between applied strain rate and diffusion rate. Using a typical value of \( D_L = 10^{-10} \text{cm}^2 \text{s}^{-1} \) and letting 250 nm be the characteristic diffusion distance, we estimate that the characteristic diffusion time is about 6 s. As long as strain rate exceeds Li+ ion diffusion rate characterized by the width of the short-circuit current signal, we observe identical current curves with similar full width at half maximum. If strain rate is slower, a current signal with extended width and reduced peak current is expected. In either case, the total energy output or repeatability is not expected to change owing to the bending rate. Similarly, slow bending frequency would allow sufficient time for Li+ ions to migrate between the electrodes and does not affect the output energy. These are demonstrated experimentally and are illustrated in Supplementary Note 6. If bent at a frequency so high that Li+ ions do not have sufficient time to migrate between electrodes, the electrodes are not able to relieve stress by lithium insertion/extraction and will eventually fail by fatigue. This is in part equivalent to low temperature condition in Nabarro–Herring creep. This frequency, however, far exceeds the human activity timescale. The device is therefore not well suited for vibrational energy harvesting at high frequency (> 100 Hz).

The energy output generated from the device in general exhibits a greater amount of current and less voltage when compared with the ceramic piezoelectric generators. Table 2 shows the comparison of peak power and energy output operated at 0.3 Hz frequency for known piezoelectric generators and our device. The piezoelectric generators cited in Table 2 have similar geometry to our device and the difference in energy output comes mainly from the material properties. The comparison is based on the area of the thin-film generators without considering film thickness, as the microstructure of the materials as well as the effect of thickness on performance differ significantly among the reported generators. In Table 2, PMN-PT (ref. 11) refers to \((1-x)\text{Pb(Mg}_{1/3}\text{Nb}_{2/3})\text{O}_3-x\text{PbTiO}_3\) and is a single crystalline thin film, while BaTiO3 (ref. 33) is a nanoparticle composite. KNLN

![Figure 5](image_url)  
**Figure 5 | Electricity generated during repeated bending tests.** (a) The open-circuit voltage at 10 mm radius of curvature and (b) short-circuit current collected during repeated bending tests at 4.0 mm radius of curvature. The nested figure shows the zoomed-in view of the 800th–807th bending cycle.

| Table 2 | Comparison of our energy harvester to piezoelectric generators in similar form factor. |
|---------|-------------------------------|-----------------|-----------------|----------------|-----------------|
|         | Active material thickness \((\mu\text{m})\) | Active area \((\text{cm}^2)\) | \(V_{oc}\) (V) | \(I_{sc}\) (\(\mu\text{A}\)) | Peak power \((\mu\text{W cm}^{-2})\) | Energy output at 0.3 Hz \((\mu\text{J cm}^{-2} \text{s}^{-1})\) |
| Our device | 0.25 × 2 | 0.63 | 0.023 | 14.5 | 0.53 | 0.476 |
| PMN-PT | 8.4 | 2.89 | 8.2 | 145 | 411 | 12.3 |
| BaTiO3 | 250 | 12 | 3.2 | 0.35 | 0.093 | 0.00278 |
| ZnO nanowire15 | 0.05 | 1 | 20 | 6 | 120 | 3.60 |
| KNLN | 250 | 9 | 12 | 1.2 | 1.60 | 0.0480 |


Device assembly and testing. The electrode prepared above was mounted onto a thin PDMS film (Sylgard 184, Dow Corning Chemical) for easy handling and encapsulation. PDMS films were prepared by mixing the elastomer with hardener at 1:1 mass ratio and curing at 65 °C for 2 h. Paraffin wax was dissolved onto PDMS as illustrated in previous report to avoid gas and vapour permeability in PDMS. When extra inhibition to gas permeation was required, for example, in repetitive bending test, the entire device was encapsulated in mylar bags often used to manufacture pouch type secondary batteries. The electrode on PI was bonded to cured PDMS by using a thin layer of uncured PDMS as glue. The electrode was then cut in half to comprise the bottom and top electrodes of the energy-harvesting device. The two electrodes were placed on top of each other, separated by a layer of electrolyte-soaked separator (Celgard 2500) and were sealed using uncured PDMS on the sides.

To eliminate any possible difference in electrochemical potential or composition between the top and bottom electrode, the two electrodes were left connected in short-circuit via external wire for at least 2 h. Bending tests were performed either by finger tapping or by servo motor (HS-796HB, Hitec). A custom repeatable bending stage was constructed using the servo motor, a 32 pitch gear (Servocity), a pinion and Arduino controller. The strain rate was ~1% per second.

References
1. Xu, S. et al. Self-powered nanowire devices. Nat. Nanotechnol. 5, 366–373 (2010).
2. Snyder, G. J. & Toberer, E. S. Complex thermoelectric materials. Nat. Mater. 7, 105–114 (2008).
3. Priya, S. & Inman, D. Energy Harvesting Technologies (Springer US, 2009).
4. Beeby, S. P., Tudor, M. J. & White, N. M. Energy harvesting vibration sources for microsystems applications. Meas. Sci. Technol. 17, R175–R195 (2006).
5. Ravindran, S. K. T., Huesgen, T., Kroener, M. & Voisard, P. A self-sustaining micro thermomechanic-pyroelectric generator. Appl. Phys. Lett. 99, 104102 (2011).
6. Anton, S. R. & Sodano, H. A. A review of power harvesting using piezoelectric materials (2003–2006). Smart Mater. Struct. 16, R1–R21 (2007).
7. Lu, M.-C., Satyanarayana, S., Karnik, R., Majumdar, A. & Wang, C.-C. A mechanical-electrokinetic battery using a nano-porous membrane. J. Micromechanics Microengineering 16, 667–675 (2006).
8. Kim, D.-K., Duan, C., Chen, Y.-F. & Majumdar, A. Power generation from concentration gradient by reverse electroodialysis in ion-selective nanochannels. Microfluid. Nanofluidics 9, 1215–1224 (2010).
9. Moon, J. K., Jeong, J., Lee, D. & Pak, H. K. Electrical power generation by mechanically modulating electrical double layers. Nat. Commun. 4, 1487 (2013).
10. Fan, F.-R., Tian, Z.-Q. & Lin Wang, Z. Flexible triboelectric generator. Nano Energy 1, 328–334 (2012).
11. Hwang, G.-T. et al. Self-powered cardiac pacemaker enabled by flexible single crystalline PMN-PT piezoelectric energy harvester. Adv. Mater. 26, 4880–4887 (2014).
12. Park, K.-I. et al. Highly-efficient, flexible piezoelectric PZT thin film nanogenerator on plastic substrates. Adv. Mater. 26, 2514–2520 (2014).
13. Wang, S. et al. Maximum surface charge density for triboelectric nanogenerators achieved by ionized-air injection: methodology and theoretical understanding. Adv. Mater. 26, 6720–6728 (2014).
14. Fan, F. R. et al. Highly transparent and flexible triboelectric nanogenerators: performance improvements and fundamental mechanisms. J. Mater. Chem. A 2, 13219 (2014).
15. Hu, Y., Lin, L., Zhang, Y. & Wang, Z. L. Replacing a Battery by a nanogenerator with 20 V Output. Adv. Mater. 24, 110–114 (2012).
16. Hill, D., Agarwal, A. & Tong, N. Assessment of Piezoelectric Materials for Roadway Energy Harvesting. California Energy Commission. Report No: CEC-500-2013-007 (DNV KEMA Energy & Sustainability, Oakland, California, USA, 2014).
17. Jeong, C. K. et al. Virus-directed design of a flexible BaTiO3 nanogenerator. ACS Nano 7, 11016–11025 (2013).
18. Jeong, C. K. et al. Topographically-designed triboelectric nanogenerator via block copolymer self-assembly. Nano Lett. 14, 7031–7038 (2014).
19. Sheldon, B. W., Soni, S. K., Xiao, X. & Qi, Y. Stress contributions to solution thermodynamics in Li-Si alloys. Electrochem. Solid State Lett. 15, A9–A11 (2011).
20. Gu, M. et al. Bending-induced symmetry breaking of lithiation in germanium nanowires. Nano Lett. 14, 4622–4627 (2014).
21. Yang, H., Liang, W., Guo, X., Wang, C.-M. & Zhang, S. Strong kinetics-driven coupling in lithiation of Si and Ge anodes. Extreme Mech. Lett. 2, 1–6 (2015).
22. He, K. et al. Transitions from near-surface to interior redox upon lithiation in conversion electrode materials. Nano Lett. 15, 1437–1444 (2015).
23. Zhao, K. et al. Lithium-assisted plastic deformation of silicon electrodes in lithium-ion batteries: a first-principles theoretical study. *Nano Lett.* 11, 2962–2967 (2011).

24. Sethuraman, V. A., Srinivasan, V., Rower, A. F. & Guduru, P. R. In situ measurements of stress-potential coupling in lithiated silicon. *J. Electrochem. Soc.* 157, A1253 (2010).

25. Ohara, S., Suziki, Z., Sekine, K. & Takamura, T. A thin film silicon anode for Li-ion batteries having a very large specific capacity and long cycle life. *J. Power Sources* 136, 303–306 (2004).

26. Cannarella, J. et al. Mechanical properties of a battery separator under compression and tension. *J. Electrochem. Soc.* 161, F3117–F3122 (2014).

27. Sim, G.-D. et al. Improving the stretchability of as-deposited Ag coatings on poly-ethylene-terephthalate substrates through use of an acrylic primer. *J. Appl. Phys.* 109, 073511 (2011).

28. Obrovac, M. N., Christensen, L., Le, D. B. & Dahn, J. R. Alloy design for lithium-ion battery anodes. *J. Electrochem. Soc.* 154, A849 (2007).

29. Zhao, K. et al. Reactive flow in silicon electrodes assisted by the insertion of lithium. *Nano Lett.* 12, 4397–4403 (2012).

30. Shenoy, V. B., Johari, P. & Qi, Y. Elastic softening of amorphous and crystalline Li–Si Phases with increasing Li concentration: A first-principles study. *J. Power Sources* 195, 6825–6830 (2010).

31. Soni, S. K., Shelden, B. W., Xiao, X., Rower, A. F. & Verbrugge, M. W. Diffusion mediated lithiation stresses in Si thin film electrodes. *J. Electrochem. Soc.* 159, A1520–A1527 (2012).

32. Hertzberg, B., Benson, J. & Yushin, G. Ex-situ depth-sensing indentation measurements of electrochemically produced Si–Li alloy films. *Electrochem. Commun.* 13, 818–821 (2011).

33. Park, K.-I. et al. Flexible nanocomposite generator made of BaTiO3 nanoparticles and graphitic carbons. *Adv. Mater.* 24, 2999–3004 (2012).

34. Nabarro, F. R. N. Steady-state diffusional creep. *Philos. Mag.* 16, 231–237 (1967).

35. Jeong, C. K., Park, K.-I., Ryu, J., Hwang, G.-T. & Lee, K. J. Large-area and flexible lead-free nanocomposite generator using alkaline niobate particles and metal nanorod filler. *Adv. Funct. Mater.* 24, 2620–2629 (2014).

36. Obrovac, M. N. & Christensen, L. Structural changes in silicon anodes during lithium insertion/extraction. *Electrochem. Solid State Lett.* 7, A93 (2004).

37. Soni, S. K., Shelden, B. W., Xiao, X. & Tokranov, A. Thickness effects on the lithiation of amorphous silicon thin films. *Scr. Mater.* 64, 307–310 (2011).

38. Ren, K., Zhao, Y., Su, J., Ryan, D. & Wu, H. Convenient method for modifying poly(dimethylsiloxane) to be airtight and resistive against absorption of small molecules. *Anal. Chem.* 82, 5965–5971 (2010).