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Authors
Stern, A
Dzero, M
Galitski, VM
et al.

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Surface-dominated conduction up to 240 K in the Kondo insulator SmB$_6$ under strain

A. Stern$^1$, M. Dzero$^2$, V. M. Galitski$^3$, Z. Fisk$^1$ and J. Xia$^1*$

SmB$_6$ is a strongly correlated mixed-valence Kondo insulator$^{1,2}$ with a newly discovered surface state$^{3,4}$, proposed to be of non-trivial topological origin$^{5,6}$. However, the surface state dominates electrical conduction only below $T^* \approx 4$ K (ref. 3), limiting its scientific investigation and device application. Here, we report the enhancement of $T^*$ in SmB$_6$ under the application of tensile strain. With 0.7% tensile strain we report surface-dominated conduction at up to a temperature of 240 K, persisting even after the strain has been removed. This can be explained in the framework of strain-tuned temporal and spatial fluctuations of f-electron configurations, which might be generally applied to other mixed-valence materials. We note that this amount of strain can be induced in epitaxial SmB$_6$ films via substrate in potential device applications.

SmB$_6$ is a prototypical Kondo insulator, a material where the quantum mechanical hybridization between the conduction and f-electronic orbitals leads to an opening of a narrow Kondo gap when a tri-piezo technique$^*$

$^*$

fashion to macroscopic crystals has been difficult until very recently near the Fermi energy $f$-electronic orbitals leads to an opening of a narrow Kondo gap when a tri-piezo technique$^*$

$^*$

which is the fractional change of the sample length $\Delta\epsilon$ decreases to zero when the surface conduction becomes larger than the bulk conduction$^*$

$^*$

suggesting that it has a similar origin to the yet unknown mechanism for pressure-induced $\Delta$ reduction$^{11}$. We note that changes in the values of $\Delta$ are much sharper when $|\epsilon| \geq 0.4\%$, suggesting a well-defined collective response for both negative and positive strain.

While compressive strain beyond $\epsilon = -0.5\%$ tends to break needle-shaped samples probably due to shear strain, much larger tensile strains can be safely applied. Shown in Fig. 2a for another (100)-oriented SmB$_6$ crystal, sample B, tensile strains up to 0.66% continuously increase the resistance saturation temperature $T^*$ up to 30 K. We note that in this sample in contrast with sample A, the surface-dominated saturation resistance is strongly dependent on applied strain, reminding us of the similarly diverse behaviours observed in high-pressure experiments$^{11,12,17,18}$ (see Supplementary Information). Surprisingly, when $\epsilon \geq 0.7\%$ we observe a dramatic onset of hysteretic behaviour in the resistivity of SmB$_6$. Note that the possibility of piezo hysteresis can be ruled out by careful experimental analysis (see Supplementary Information on...
Up to this point we have presented experimental observation of two effects: surface-dominated transport in SmB$_6$, at temperatures above 200 K and hysteresis in resistivity under an application of tensile strain. To provide the qualitative understanding of the observed phenomena, we recall that it has been well established experimentally$^{21,22}$ that SmB$_6$ belongs to a class of intermediate valence systems: the $f$-orbital electronic configuration of samarium ions fluctuates between the $4f^5$ and $4f^6$ states on a typical timescale $\tau_{ivc}$ across a fairly wide temperature range. Experiments that probe the samarium valence on a timescale longer than $\tau_{ivc}$ will observe an intermediate valence state$^{21,22}$. Experimentally found values of an intermediate valence configuration vary slightly between Sm$^{2+}$ and Sm$^{3+}$, suggesting that the energies for the corresponding integer valence configurations are comparable to each other, $E(f^6) \sim E(f^5)$.

With a decrease in temperature, emerging hybridization between the $d$-orbital and $f$-orbital states of samarium opens up a scattering channel $4f^6 \rightarrow 4f^5 + 5d$ leading to an onset of insulating behaviour at low temperatures and also to small changes in the intermediate valence configuration$^{21,22}$. Since the ionic volume corresponding to the $4f^6$ configuration exceeds the one for the $4f^5$ configuration, the energy difference between the corresponding valence configurations $\Delta E = E(f^6) - E(f^5)$ will increase with pressure and the scattering processes $4f^6 \rightarrow 4f^5 + 5d$ will be suppressed. As a consequence, one expects that the material recovers its metallic properties in the bulk. On the other hand, an application of a tensile strain acts as a negative pressure and therefore should have an opposite effect of enhancing the insulating behaviour and promoting stronger hybridization between the $d$- and $f$-orbitals.

discussion of this issue). As shown in Fig. 2b with sample A, at an elevated temperature of 30 K and at tensile strains $\epsilon \geq 0.7\%$ the resistance increases suddenly by more than two orders of magnitude from the bulk-dominated resistance of 1 $\Omega$ to the surface-dominated resistance of $\sim 100 \Omega$, indicative of a first-order phase transition. This dramatic phenomenon is hysteretic in nature: when the strain is reduced to 0% the sample resistance maintains its surface-dominated value until a compressive strain is applied. However, after an application of a large tensile strain, the bulk of SmB$_6$ remains insulating with a significantly increased temperature $T^*$ even after the strain is removed.

To measure the upper bound of $T^*$—the temperature below which the surface conduction is dominant—we prepared sample C. This sample has been strained at low temperature with $\epsilon = 0.9\%$, the strain was reduced back to zero and the sample was warmed up to 300 K. It is shown in Fig. 2c, where the blue curve represents the initial cool down without strain and the red curve shows the warm up after the tensile strain has been applied at low temperature. The noise in the resistance value at temperatures between 40 K and 240 K is quite repeatable between measurements, suggestive of an underlying fluctuations in the system, which will be discussed below. The sample resistance remains to be more than three orders of magnitude larger than the bulk-dominated value (blue curve) normally observed at these temperatures until the temperature reaches $T^* = 240$ K when it suddenly reverts back to the bulk resistance value of 0.07 $\Omega$. To our knowledge, this $T^*$ is over double the observed value in topological insulator films of Bi$_2$Se$_3$ (ref. 19) and Bi$_2$Te$_3$Se (ref. 20).

**Figure 1** | Experimental set-up and gap enhancement with tensile strain in sample A. a. Sketch and photo of the strain apparatus with a SmB$_6$ sample (more details in Supplementary Information). b. The resistance of a (100)-oriented crystal as a function of inverse temperature when subject to a relatively small strain between $-0.4\%$ and 0.5%. The dashed lines are linear fits. The extracted bandgap $\Delta$ is measured from the slope of the curve (dashed line) in the bulk-dominated conduction region. c. The extracted bandgap, which increases with tensile strain and decreases with compressive strain. The blue dot is the $\Delta$ of the strain-free state before the sample is mounted to the stain set-up.
**Figure 2** | Hysteresis and room-temperature surface-dominated conduction.  

a. The enhancement of $T^*$ with tensile strain $\epsilon \leq 0.66\%$ in sample B. Unlike sample A the low-temperature saturation (surface) resistance in this sample is strain dependent, similar to what was found under pressure in ref. 11.  

b. The occurrence of hysteresis with $\epsilon \geq 0.6\%$ in sample A. Data shown here represent measurements after the sample has been strained beyond 0.7%.  

c. The persistence of surface-dominated conduction up to 240 K, after a strain of $\epsilon = 0.9\%$ was applied and then removed at low temperature in sample C.

**Figure 3** | Temperature–strain phase diagram.  

a. A schematic illustration of strain-induced transition from temporal fluctuating mixed-valence state to spatially heterogeneous-valence state.  

b. A reconstructed phase diagram of SmB$_6$ under strain with data from this paper as well as pressure data from refs 11,12. The left axis corresponds to the bandgap data in ref. 12 (open red triangles), the bandgap data in ref. 11 (open red squares), and our own bandgap data (red circles). The right axis corresponds to only $T^*$, which is shown in blue downturntriangles.
Our experimental results for the small tensile strain confirm these expectations.

While an increase in $T^*$ with tensile strain can be qualitatively understood by the argument based on the changes in the ionic volume, our observation of hysteresis in resistivity as a function of temperature points towards the emergence of the spatial inhomogeneities. Since the energies of the Sm$^{+4}$ and Sm$^{3+}$ become almost degenerate the characteristic timescale $\tau_{ivc}$ will increase. Ultimately, $\tau_{ivc} \to \infty$ and the system is expected to develop spatially inhomogeneities by becoming mixed-valent: each samarium ion will be in either the Sm$^{+4}$ or Sm$^{3+}$ integer valence state, as we have schematically shown in Fig. 3a. Accordingly we constructed a phase diagram shown in Fig. 3b: it illustrates the change for surface conduction. Note, however, as was discussed in ref. 23, transition into the spatially inhomogeneous state would be energetically costly since it would mean the departure from the simple rock salt crystal structure. However, in our experiments the energy costs are offset by a tensile strain. Finally, we note that an abrupt jump in the value of $T^*$ signals the first-order transition; however, its value is most probably affected by the local strain and Coulomb interactions between electrons in the Sm$^{+4}$ and Sm$^{3+}$ valence states, so that this change in $T^*$ may not reflect the corresponding changes in the bulk hybridization gap.

Most recently, SmB$_6$ has been discussed as a prominent candidate for the first correlated topological insulator. One of the major experimental issues with identifying the topological nature of the metallic surface states has been the smallness of the insulating gap precluding, for example, the precise measurement of the surface electron’s chirality. Our experimental findings show that this issue can be, in principle, resolved. On a more general note, our results may not reflect the conventional magnetism in the intermediate-valence compound SmB$_6$. Phys. Rev. B 77, 193107 (2008).

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Author contributions
A.S. performed the measurements. M.D. and V.M.G. developed the theory. J.X. designed the project. All authors discussed the result, and contributed to the writing of the manuscript.

Additional information
Supplementary information is available in the online version of the paper. Reprints and permissions information is available online at www.nature.com/reprints. Publisher’s note: Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations. Correspondence and requests for materials should be addressed to J.X.

Competing financial interests
The authors declare no competing financial interests.

References
Methods

Single-crystal growth. All samples were grown by the aluminium flux method and HCl was used to remove any aluminium flux or impurities on the samples. Samples were selected on the basis of their dimensions, which was possible due to the abundance of SmB$_6$ samples at our disposal. Samples were then polished to remove any surface cracks, which can cause the samples to break prematurely.

Strain apparatus. The strain apparatus is composed of titanium and piezo stacks to limit the effects of thermal contraction/expansion shown in Supplementary Information, Fig. 1. All of the piezo movement is applied to a narrow gap where the sample is mounted using Stycast 2850FT epoxy with catalyst 24 LV. Strain gauges were mounted on the piezo stacks and calibrated using an optical microscope at low temperatures.

Transport measurement. We measured resistance using a Signal Recovery 7225 DSP lock-in amplifier. The corresponding gap $\Delta$ is obtained by fitting the bulk-dominated conduction region to $R = R_{\text{bulk}} \exp(\Delta/k_B T)$, where, $R_{\text{bulk}}$ is a resistance constant for the bulk, $T$ is the temperature, $R$ is the measured resistance, and $\Delta$ is the bandgap.

Data availability. The data that support the findings of this study are available from the corresponding author on reasonable request.