Surface Hall Effect and Nonlocal Transport in SmB_6: Evidence for Surface Conduction

Supplemental information:

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When both surface and bulk contribute to electric conduction, the electric transport can be treated with a two-band model. Assuming the simplest case of one surface conduction channel (top and bottom surfaces combined) with Hall coefficients R_{HS} and resistivity ρ_S, and one bulk channel with Hall coefficients R_{HB} and resistivity ρ_B, the Hall resistance $R_{xy} = V_{xy}/I$ is :

$$R_{xy} = [(R_{HS}\rho_B^2 + R_{HB}\rho_S^2 d)B + R_{HS}\, R_{HB}\, (R_{HS}d + R_{HB}\,)\, B^3]\, /\, [(\rho_S d + \rho_B)^2 + (R_{HS}d + R_{HB})^2\, B^2]$$

Nonlinearity is expected at large B, but at small fields it simplifies to:

$R_{xy} = B(R_{HS}\rho_B^2 + R_{HB}\rho_S^2 d)/\,(\rho_S d + \rho_B)^2$, which is linear with magnetic field.

To first order, we assume in SmB_6 the transport is governed by a temperature dependent bulk channel, and a temperature independent surface channel. Note that it is still possible to have multiple surface channels, thus we take the effective 2D resistivity as ρ_S, and Hall resistance as

R_{HS}, but can't infer carrier density or mobility until more information is known on the surface carrier types (electrons, holes or both). Here ρ_S and R_{HS} are from both top and bottom surfaces combined. The bulk is treated as a gapped insulator with an indirect activation gap $\Delta = 38\ K$, as calculated from temperature dependence of Hall effect at high temperatures. The bulk carrier density n_B thus follows the activation law of an insulator: $n_B = n_B^0 \exp(-\Delta/k_BT)$, where k_B is the Boltzmann's constant and n_B^0 is a constant. In the simplified case of temperature independent mobility, the Hall coefficient and longitudinal resistivity are inversely proportional to n_B, giving activated Hall coefficient $R_{HB} = R_{HB}^0 \exp(\Delta/k_BT)$ and resistivity $\rho_B = \rho_B^0 \exp(\Delta/k_BT)$.

For a sample with length, width and thickness of L, w, and d respectively. The longitudinal resistance is just the parallel resistance of the surface and bulk channels:

$$R_{xx} = \frac{L}{w\,(1/\rho_S + d\,/\rho_B)} = \frac{L}{w\,(1/\rho_S + d/\rho_B^0 \exp(\Delta/k_BT))}$$

And the Hall resistance in the small field limit is:

$$R_{xy} = B(R_{HS}\rho_B^2 + R_{HB}\rho_S^2 d)/\,(\rho_S d + \rho_B)^2$$

$$= B\ (R_{HS}(\rho_B^0 \exp\left(\frac{\Delta}{k_BT}\right))^2 + R_{HB}^0 \exp(\Delta/k_BT)\rho_S^2 d)/\ (\rho_S d + \rho_B^0 \exp(\Delta/k_BT))^2$$

$$= B\ (R_{HS}(\rho_B^0)^2 + R_{HB}^0 \rho_S^2 d \exp(-\Delta/k_BT))/\ (\rho_S d \exp(-\Delta/k_BT) + \rho_B^0)^2$$

Using this simple model we could calculate temperature dependences of R_{xx} and R_{xy}/B, e.g. as shown in Fig. S1. We could also perform finite element simulations for the transport in more complicated geometries. Fig. S2 and Fig. S3 show the simulated surface potential profiles at $300\ K$ and $0\ K$ for the nonlocal transport experiment in a sample with thin plate geometry. The simulation curves in Fig. 2 in the main text are generated using this finite element simulation. The dimensions used in the simulation are illustrated in Fig. S4.

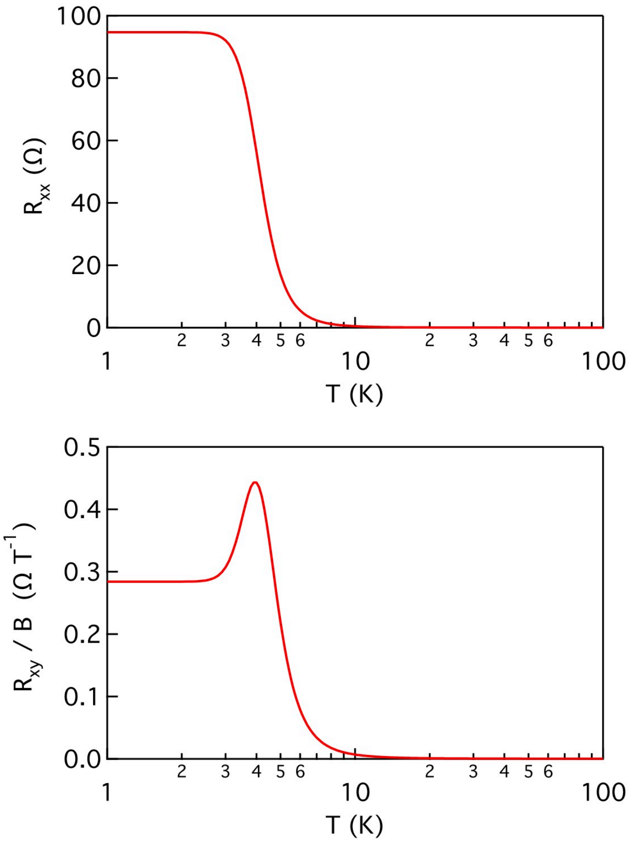

Figure S1 | Simple Transport Model. a, b, Calculated R_{xy} and R_{xx} using the simple model of two channel conduction.

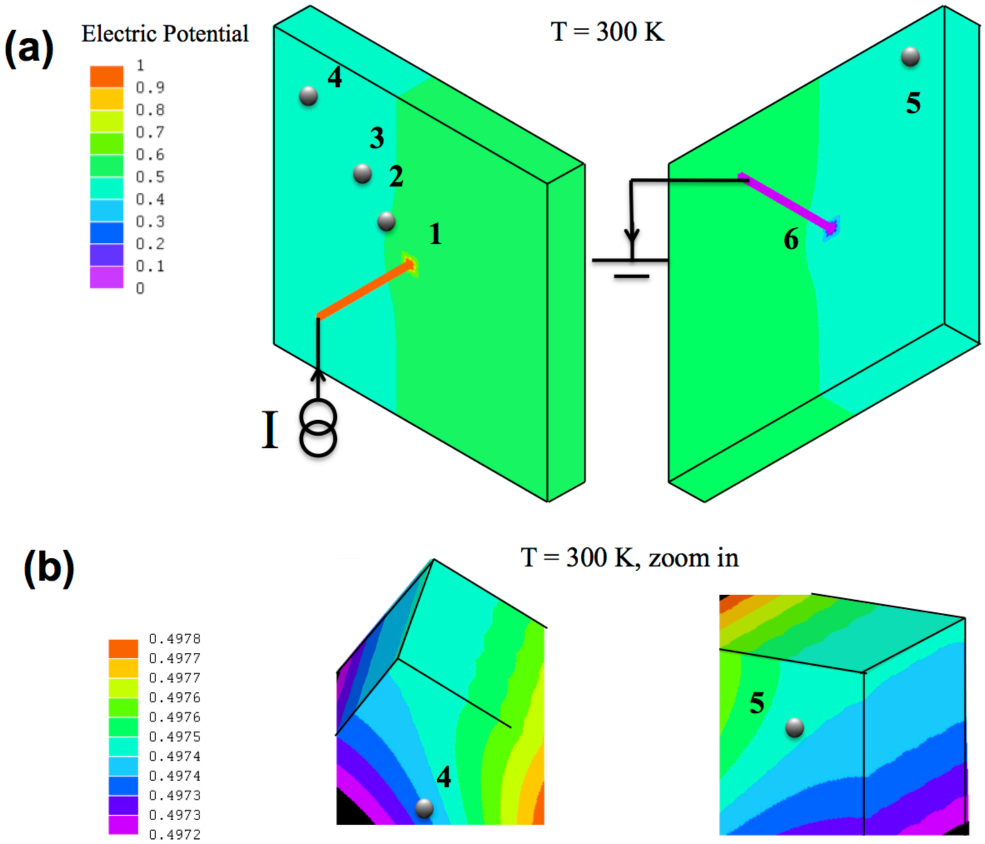

Figure S2 | Simulation of Nonlocal Transport at 300 K. a, Finite elements simulation of the surface potential profile in the nonlocal transport. As the conduction is dominated by the bulk, the nonlocal voltage V_{45} is much smaller than V_{23}. **b,** Zoom in views for contacts 4 and 5, showing that V_{45} is a small negative value due to slight misalignment of contacts.

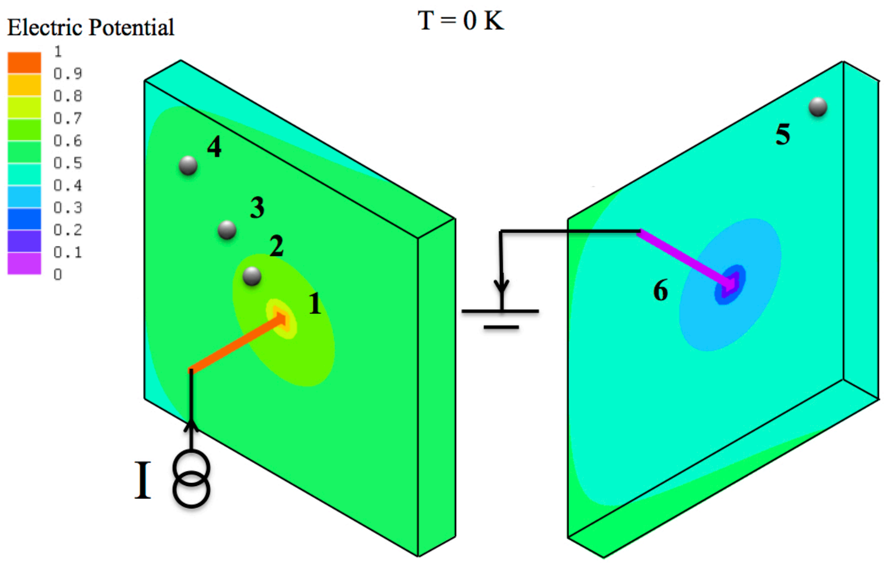

Figure S3 | Simulation of Nonlocal Transport at 0 K. a, Finite elements simulation of the surface potential profile in the nonlocal transport. Due to surface conduction, the nonlocal voltage V_{45} is large and is comparable to V_{23}.

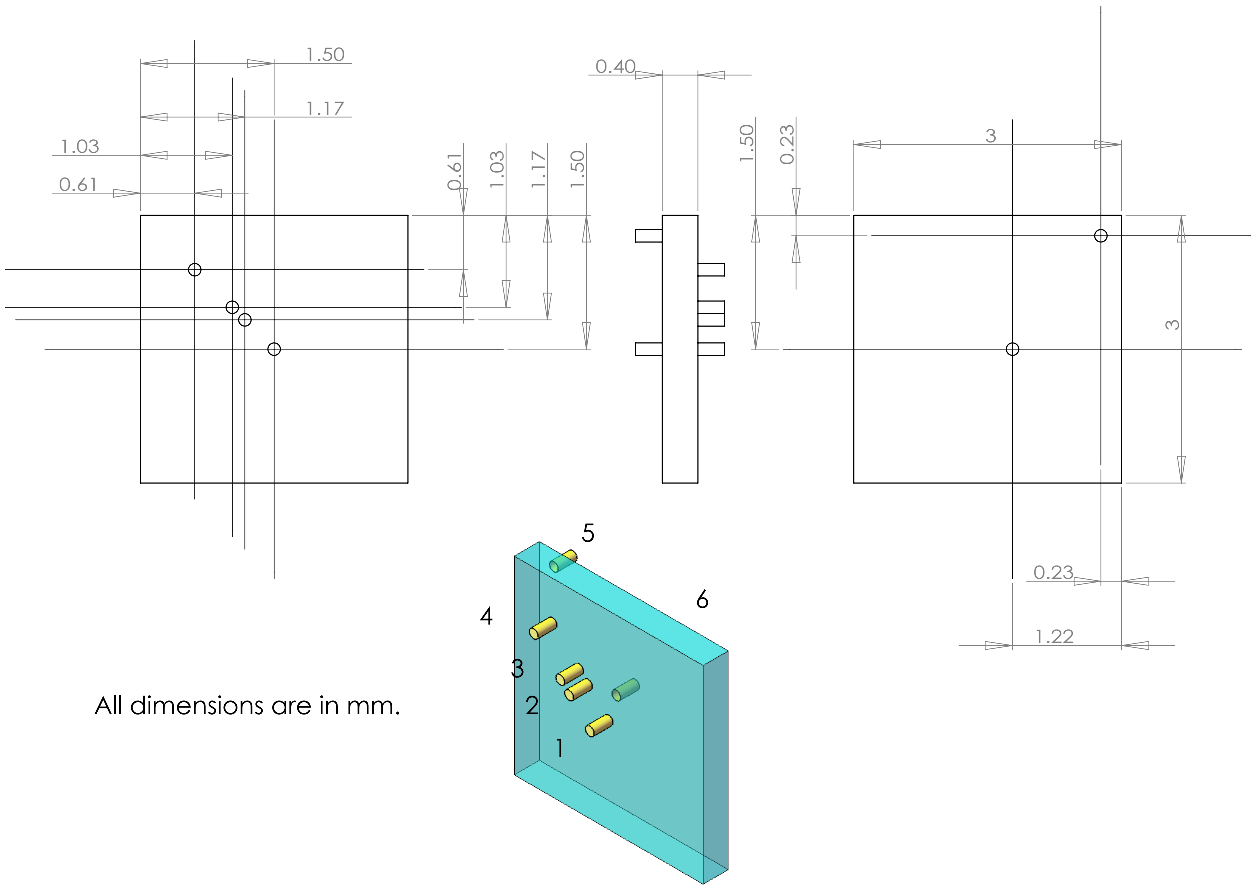

Figure S4 | Sample and contact dimensions used in simulation of Nonlocal Transport.