Supporting information for

Magnetic Doping and Kondo Effect in Bi$_2$Se$_3$

Nanoribbons

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SEM images of VLS-grown Bi$_2$Se$_3$ nanoribbons using Fe-Au and Ni-Au thin films

Using Fe-Au and Ni-Au thin films as catalysts for the VLS growth of Bi$_2$Se$_3$ nanoribbons, we obtain two distinct morphologies in the case of Fe-Au thin films and three distinct morphologies in the case of Ni-Au thin films. For Fe-doped Bi$_2$Se$_3$ nanoribbons, we observe wide nanoribbons (Fig. S1(c,d)) and narrow, long nanoribbons (Fig. S1(e,f)). For Ni-doped Bi$_2$Se$_3$ nanoribbons, we observe wide nanoribbons (Fig. S1(j)), narrow, long nanoribbons (Fig. S1(h)), and nanorods with rough side surfaces (Fig. S1(g,i)). The nanorods consist of thin platelets that are stacked together along the axis of the nanowire.
Fig S1. SEM images of VLS-grown Bi$_2$Se$_3$ nanoribbons using Fe-Au thin films (a, c, d, e, f) and Ni-Au thin films (b, g, h, i, j).

**EDX spectra and maps of a Bi$_2$Se$_3$ nanoribbon**

By acquiring EDX spectra from the Bi$_2$Se$_3$ nanoribbons, we confirm that the atomic ratio of Bi/Se is 2/3 within the accuracy of the measurements. Figure S2 shows EDX spectra obtained from the region of the ribbon (spectrum in green) and the metal particle (spectrum in blue), grown using a Fe-Au thin film. The inset shows the TEM image of the ribbon from which EDX spectra were acquired. By integrating the intensity under Bi and Se peaks in the red boxed region, we see that Bi:Se = 40%:60%. The EDX spectrum from the metal particle shows Au and Fe signals. Ni signal is present in both spectra, which we believe comes from the microscope such as the magnetic lenses (For high energy x-rays, x-ray fluorescence range can be large. So, fluorescence from the sample holder, apertures in the scope, and etc. can contribute to the EDX...
signals significantly. For Fe, we know the Fe signal obtained in the metal particle is from the particle because the Fe signal is absent when the EDX spectrum was obtained from the ribbon, which should not be the case if the Fe-signal was from the microscope).

Fig S2. Atomic ratio analysis of Bi to Se in the Bi$_2$Se$_3$ nanoribbons. The inset shows the ribbon that was analyzed. The spectrum in blue is obtained from the metal particle while the spectrum in green is obtained from the ribbon region only. The red dotted region indicates Bi and Se peaks that were used to calculate the atomic ratio of Bi to Se.

In the case of using Ni-Au thin films as catalysts, we sometimes observe compound catalyst particles that contain only Ni and Se signals, without Au signals. Figure S3 shows elemental maps of a nanoribbon with one such metal particle. The co-presence of Ni and Se in the catalyst particle indicates that Se reacts with Ni to form a Ni-Se compound, showing facets in dark field STEM images. We did not detect any Au signals in this metal particle.
Fig S3. Elemental maps of Ni, Se, and Bi obtained from a EDX scan in scanning TEM mode. (a) shows an annular dark field STEM image of a Bi$_2$Se$_3$ nanoribbon. (b), (c), and (d) are Ni, Se, and Bi elemental maps obtained from the nanoribbon and the metal particle. The RGB plot, where Ni is green (G), Se is red (R), and Bi is blue (B), is shown in (f). Yellow in the RGB color scheme is a mix of green and red, thus we see that the metal catalyst is a Ni-Se compound. The ribbon appears in purple, which is a mix of blue (Bi) and red (Se), confirming that it is Bi$_2$Se$_3$.

**Magneto-transport measurements of un-doped and Fe-doped Bi$_2$Se$_3$ nanoribbons at low temperature**

To confirm the presence of active magnetic dopants in Bi$_2$Se$_3$ nanoribbons, careful transport studies were carried out at low temperatures of un-doped and Fe-doped Bi$_2$Se$_3$ nanoribbon devices. In the case of un-doped Bi$_2$Se$_3$ nanoribbons, a clear weak antilocalization effect is observed (Fig. S4(c,d)) due to the intrinsic spin-orbit interactions, which are also responsible for the topological nature of the conducting surface states. However, in the case of Fe-doped Bi$_2$Se$_3$
nanoribbons, we do not observe a clear weak antilocalization effect (Fig. S5 (c,d)). Note that the quantum correction to the conductivity arising from weak antilocalization is ten times smaller in the Fe-doped Bi$_2$Se$_3$ nanoribbon device (Fig. S5(d)) as compared to the un-doped Bi$_2$Se$_3$ nanoribbon device (Fig. S4(d)).

Fig S4. (a) Temperature-dependent, four-point resistance of an un-doped Bi$_2$Se$_3$ nanoribbon. (b) Magnetoresistance of the nanoribbon as a perpendicular magnetic field is applied. (c) Weak antilocalization effect is observed in the magnetoresistance of the nanoribbon as a magnetic field parallel to the current flow is applied. (d) Change in conductance in the quantum conductance unit of the data shown in (c).
Fig S5. (a) Temperature-dependent, four-point resistance of a Fe-doped Bi$_2$Se$_3$ nanoribbon, showing a clear Kondo behavior. The inset shows the corresponding device. The top gate was used to obtain an ensemble average curve that is shown in (d). (b) Magnetoresistances of the Fe-doped nanoribbon as a perpendicular magnetic field is applied at 4K, 2K, and 260 mK. (c) Weak antilocalization effect is not clearly seen in the magnetoresistance measurements of the Fe-doped nanoribbon as a magnetic field parallel to the current flow is applied. (d) Change in conductance in the quantum conductance unit as a function of the magnetic field. The plot is an ensemble average obtained by averaging measurements acquired at different gate voltages.