Topological Superconductivity in $Cu_xBi_2Se_3$

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A topological superconductor (TSC) is characterized by the topologically protected gapless surface state that is essentially an Andreev bound state consisting of Majorana fermions. While a TSC has not yet been discovered, the doped topological insulator $Cu_xBi_2Se_3$, which superconducts below ~3 K, has been predicted to possess a topological superconducting state. We report that the point-contact spectra on the cleaved surface of superconducting $Cu_xBi_2Se_3$ present a zero-bias conductance peak (ZBCP) which signifies unconventional superconductivity. Theoretical considerations of all possible superconducting states help us conclude that this ZBCP is due to Majorana fermions and gives evidence for a topological superconductivity in $Cu_xBi_2Se_3$. In addition, we found an unusual pseudogap that develops below ~20 K and coexists with the topological superconducting state.

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Tunneling Conductance and Surface States Transition in Superconducting Topological Insulators

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We develop a theory of the tunneling spectroscopy for superconducting topological insulators (STIs), where the surface Andreev bound states (SABSs) appear as helical Majorana fermions. Based on the symmetry and topological nature of parent topological insulators, we find that the SABSs in the STIs have a profound structural transition in the energy dispersions. The transition results in a variety of Majorana fermions, by tuning the chemical potential and the effective mass of the energy band. We clarify that Majorana fermions in the vicinity of the transitions give rise to robust zero bias peaks in the tunneling conductance between normal metal/STI junctions.

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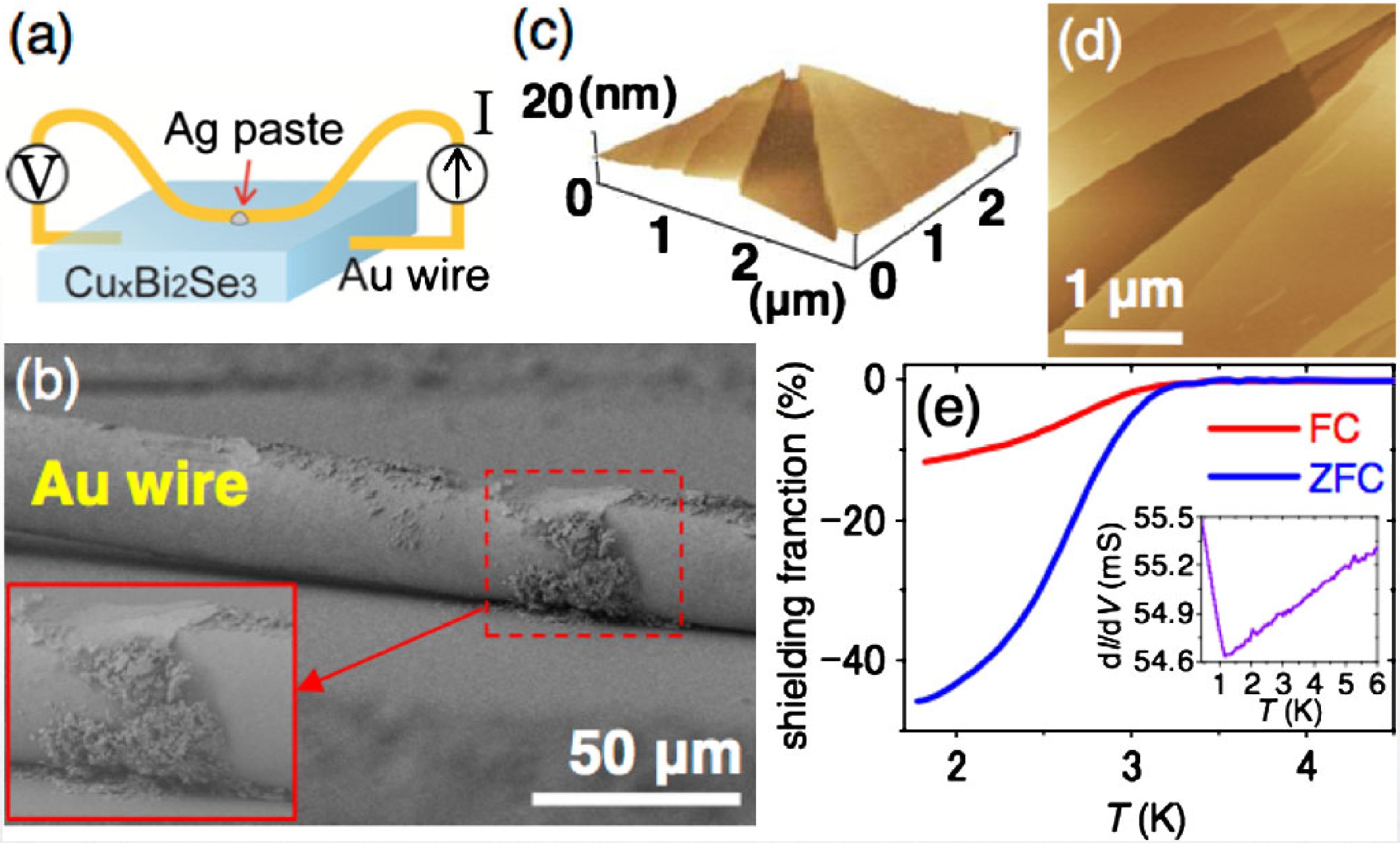
Bi_2Se_3

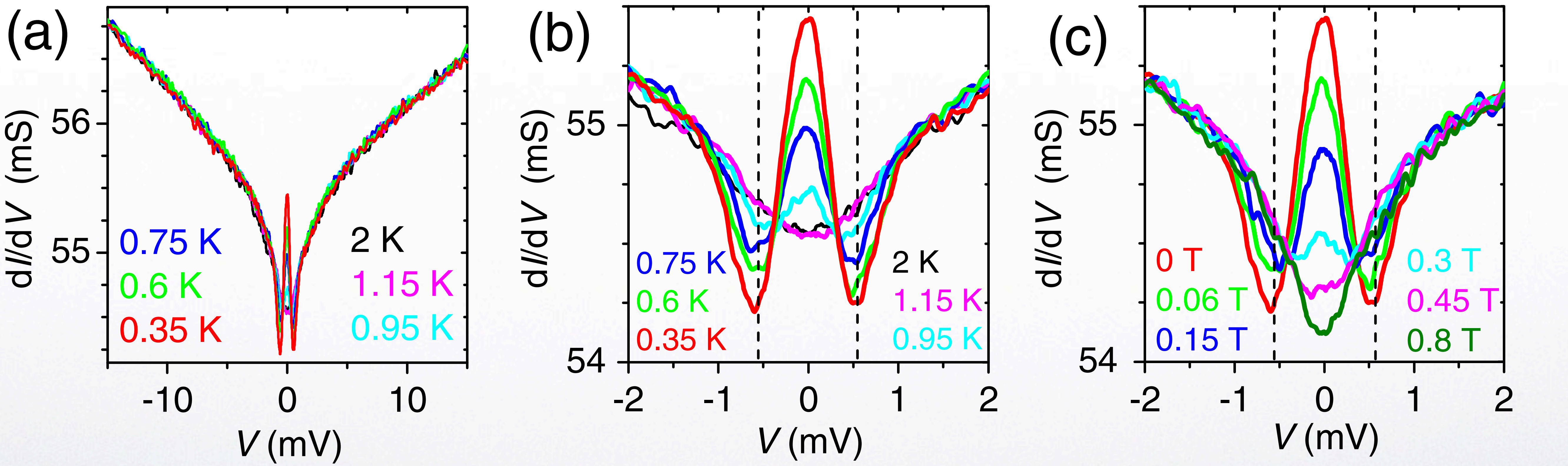
Topological Insulator (TI) with topologically protected gapless Dirac fermions on its surface

intercalation of Cu (x~0.3)

$Cu_xBi_2Se_3$

Candidate Topological Superconductor (TSC)


(a)
Ag paste
I
V
CuxBi2Se3
Au wire
(c)
20 (nm)
0
1
2
(μm)
0
1
2
(d)
1 μm
(b)
Au wire
50 μm
(e)
FC
ZFC
shielding franction (%)
0
−20
−40
2
3
4
T (K)
dI/dV (mS)
55.5
55.2
54.9
54.6
1 2 3 4 5 6
T (K)



(a)
56
55
dI/dV (mS)
0.75 K
0.6 K
0.35 K
2 K
1.15 K
0.95 K
-10
0
10
V (mV)
(b)
55
54
dI/dV (mS)
0.75 K
0.6 K
0.35 K
2 K
1.15 K
0.95 K
-2
-1
0
1
2
V (mV)
(c)
55
54
dI/dV (mS)
0 T
0.06 T
0.15 T
0.3 T
0.45 T
0.8 T
-2
-1
0
1
2
V (mV)

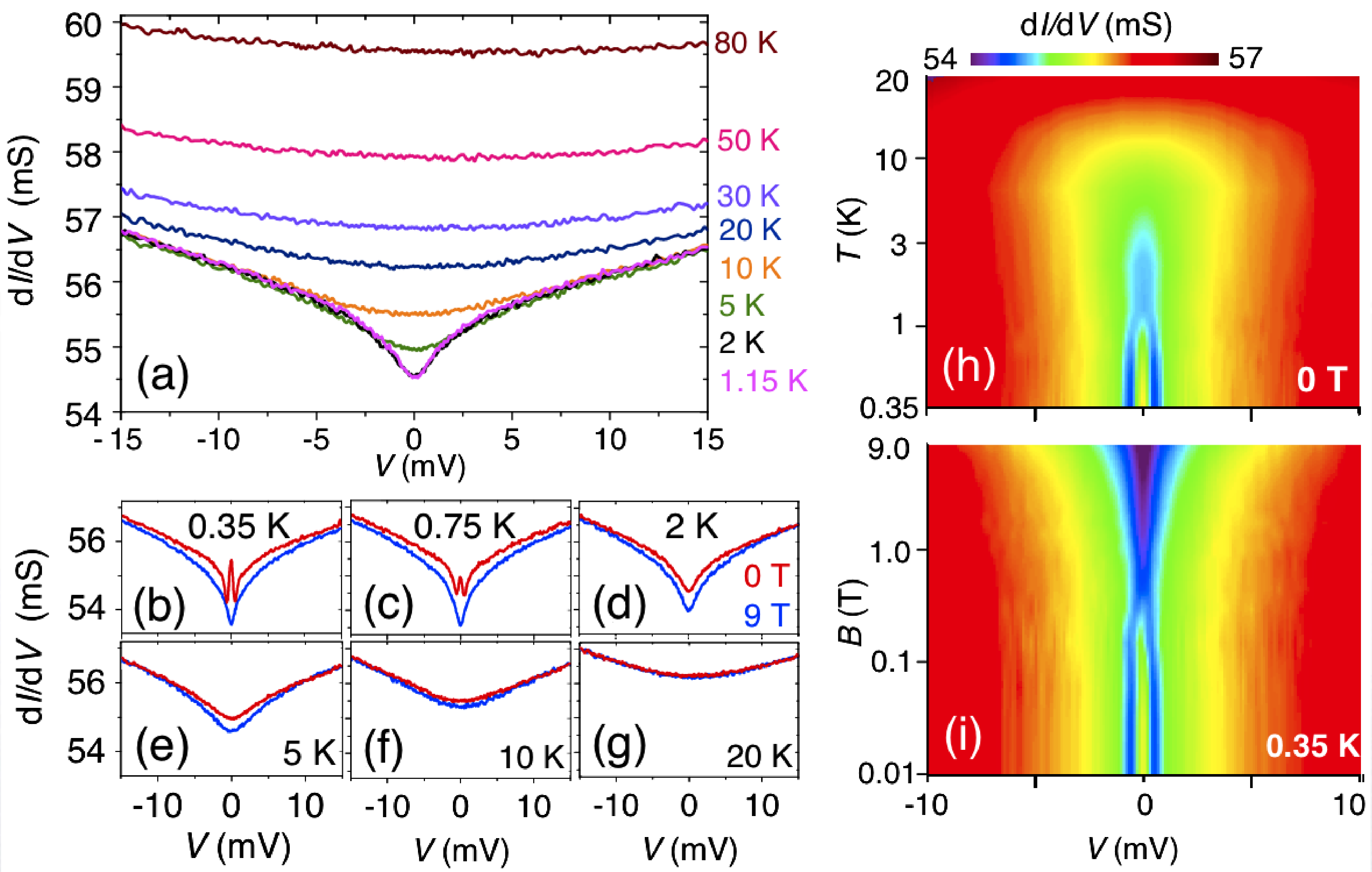
Possible explanations:

-Andreev reflection

-reflectionless tunneling

-magnetic scattering

-unconventional Andreev bound states (ABS)



dI/dV (mS)
54
57
60
59
58
57
56
55
54
80 K
50 K
30 K
20 K
10 K
5 K
2 K
1.15 K
(a)
- 15
-10
-5
0
5
10
15
V (mV)
0.35 K
0.75 K
2 K
0 T
9 T
(b)
(c)
(d)
(e)
(f)
(g)
5 K
10 K
20 K
T (K)
20
10
3
1
0.35
(h)
0 T
B (T)
9.0
1.0
0.1
0.01
(i)
0.35 K
-10
0
10

$$H_{\mathrm{TI}}(\boldsymbol{k}) = m\sigma_x + v_z k_z \sigma_y + v\sigma_z (k_x s_y - k_y s_x),$$

$$m = m_0 + m_1 k_z^2 + m_2 (k_x^2 + k_y^2)$$

$$(m_1 m_2 > 0)$$

s_μ, σ_μ Pauli matrices in spin and orbital spaces

Bogoliubov-de Gennes (BdG) Hamiltonian in Nambu representation

$$\left(\psi_{\sigma\uparrow}, \psi_{\sigma\downarrow}, -\psi^{\dagger}_{\sigma\downarrow}, \psi^{\dagger}_{\sigma\uparrow}\right)$$

$$H_{\mathrm{STI}}(\boldsymbol{k}) = (H_{\mathrm{TI}}(\boldsymbol{k}) - \mu)\tau_z + \hat{\Delta}\tau_x,$$

six independent pairings:

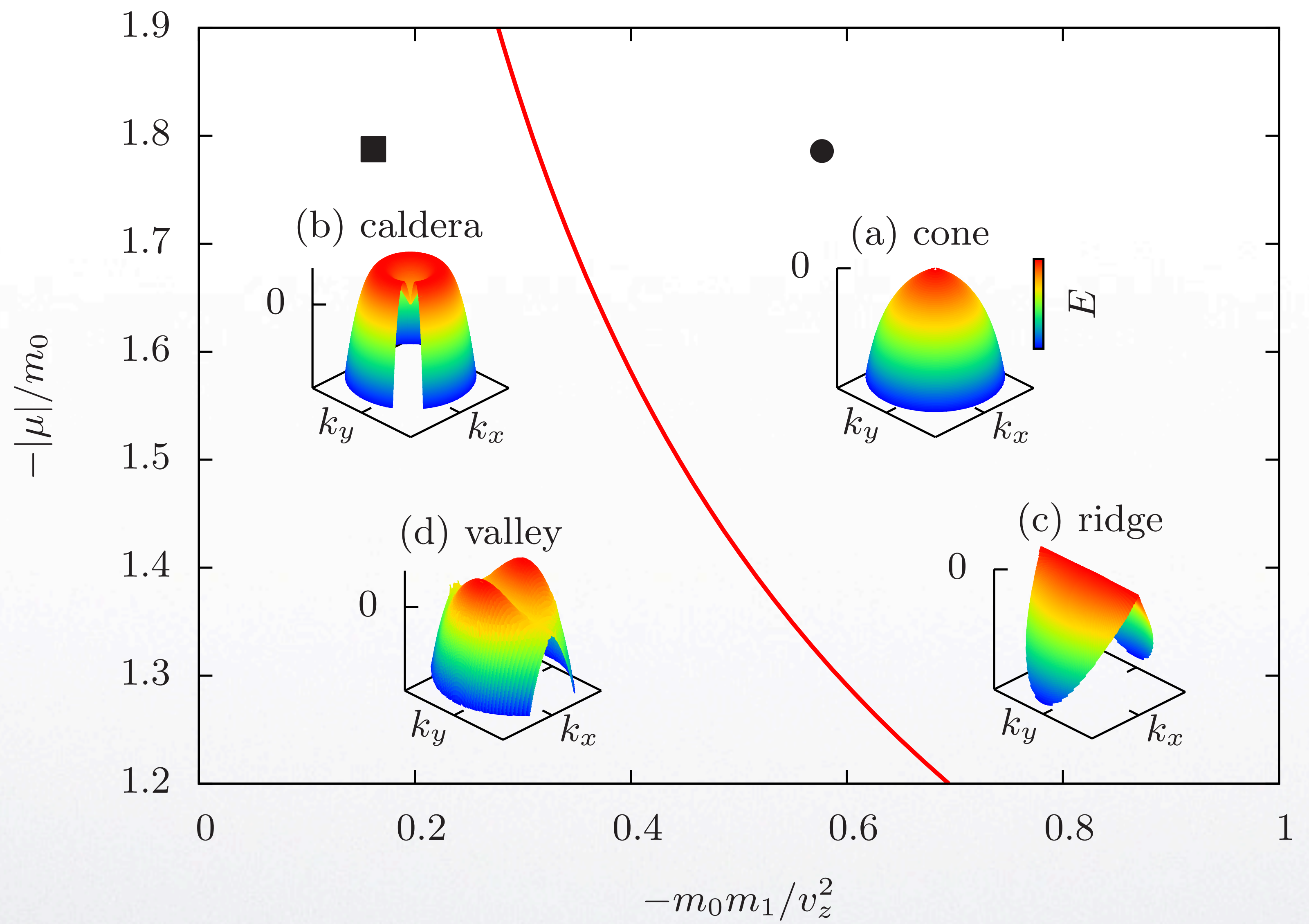
$$\Delta = s_y \Delta^T s_y \longrightarrow (\Delta, \Delta\sigma_x, \Delta\sigma_z, \Delta\sigma_y s_x, \Delta\sigma_y s_y, \Delta\sigma_y s_z)$$

Surface Andreev Bound State

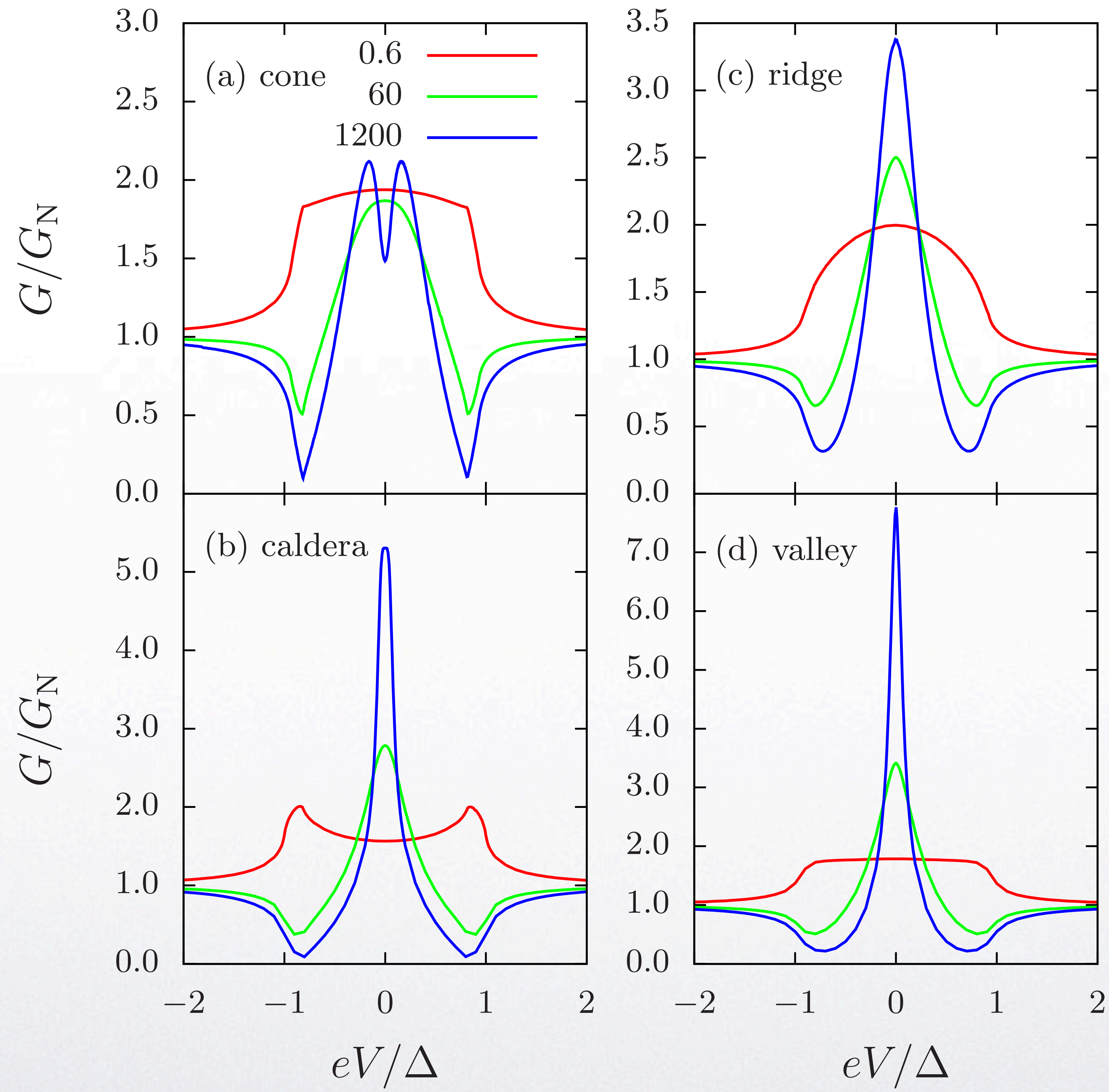
$$\psi_{\mathrm{STI}}(z>0) = \sum_I t_I u_I e^{iq_I z} e^{ik_x x} e^{ik_y y}$$

$$\begin{cases} E(k_x, k_y, q_I) = E \\ E(k_x, k_y, q_I)/\partial q_I > 0 \\ \text{or } \mathrm{Im} q_I > 0 \\ \psi_{\mathrm{STI}}(z=0) = 0 \end{cases}$$

Only $(\Delta\sigma_y s_x, \Delta\sigma_y s_y, \Delta\sigma_y s_z)$ give gapless localized SABS



1.9
1.8
1.7
1.6
1.5
1.4
1.3
1.2
0
0.2
0.4
0.6
0.8
1
$-|\mu|/m_0$
$-m_0 m_1/v_z^2$
(b) caldera
(a) cone
(d) valley
(c) ridge
E
k_y
k_x



(a) cone
0.6
60
1200
(b) caldera
(c) ridge
(d) valley
G/G_N
G/G_N
eV/Δ
eV/Δ