Coshare Science
Where Video Meets Academia

TOPICAL REVIEW

Surface and edge states of quantum materials

Shuji Hasegawa

Department of Physics, University of Tokyo, Japan

https://doi.org/10.61109/cs.202502.137

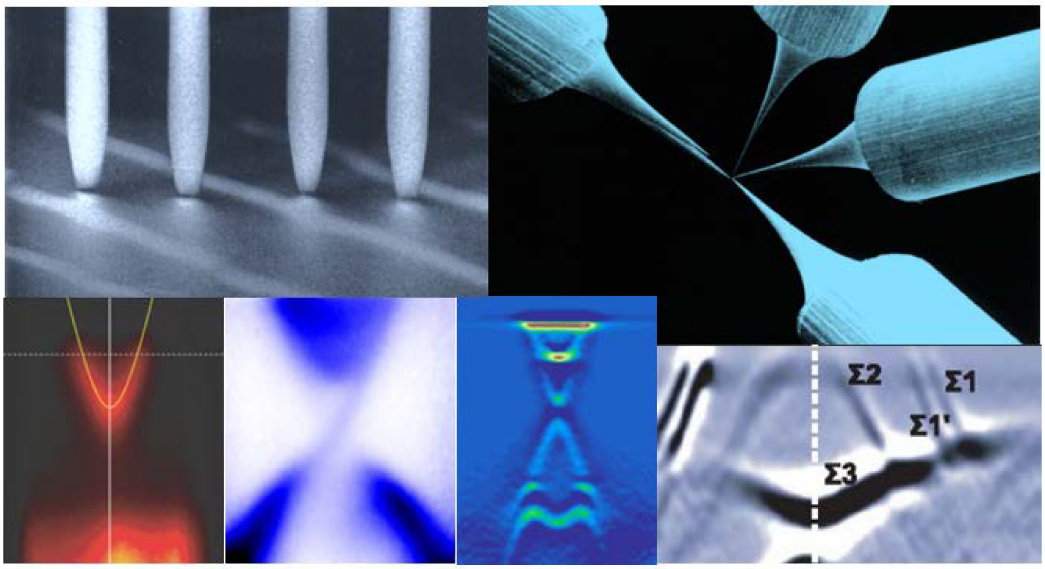
Citation: S. Hasegawa, Surface and edge states of quantum materials, *Coshare Science* **03**, 01 (2025)

Author introduction

Shuji Hasegawa is a professor at Department of Physics, University of Tokyo. He is also the President of The Physical Society of Japan in April 2023-March 2025. His specialty is experimental condensed matter physics, especially surface physics.

Highlights

This video review article introduces atomic structures, electronic states, and transport properties which are characteristic to crystal surfaces, and their intentional modifications. The surface states are an important playground for novel and rich physics of two-dimensional materials and topological materials.



Coshare Science
·Physics·
https://doi.org/10.61109/cs.202502.137
TOPICAL REVIEW

Surface and edge states of quantum materials

Shuji Hasegawa

Department of Physics, University of Tokyo, Japan

Abstract Electronic states at surfaces, interfaces, and edges of materials emerge due to different reasons and have their own characters, which are expected to be useful for intriguing physics and possible applications to electronic/spintronics devices. Especially emerging quantum materials, such as graphene and similar monatomic-layer materials, van der Waals two-dimensional crystals, and topological insulators, show prominent features in the surface/edge states. Such states at the boundaries are different from those inside the three- or two-dimensional crystals, because of the truncation of crystal lattice periodicity, space-inversion-symmetry breaking, and difference in topology in band structures across the boundaries. Such quantum materials are expected to be key ingredients for energy-saving/-harvesting technology as well as quantum computation/information technology. This is based on exotic phenomena at the states, such as spin–momentum locking of electrons, dissipation-less charge/spin currents, nonreciprocal current, and possible Majorana fermions. In this presentation, the fundamental concepts of such surface/edge states are introduced from the viewpoint of surface physics. Especially charge and spin-related transport properties are discussed based on controls of the atomic and electronic structures of materials by using state-of-the-art techniques.

Keywords surface states, surface structures, surface transport, graphene, topological insulators, super lattices, epitaxial growth

References

1. S. Hasegawa, Surface and interface physics driven by quantum materials, *Appl. Phys. Express* **17**, 050101 (2024).
2. S. Hasegawa and F. Grey, Electronic transport at semiconductor surfaces—from point-contact transistor to micro-four-point probes, *Surf. Sci.* **500**, 84 (2002).
3. H. Aizawa, M. Tsukada, N. Sato, and S. Hasegawa, Asymmetric structure of the Si(111)-3×3-Ag surface, *Surf. Sci.* **429**, L509 (1999).
4. T. Hirahara, I. Matsuda, M. Ueno, and S. Hasegawa, The effective mass of a free-electron-like surface state of the Si(111)3×3-Ag surface investigated by photoemission and scanning tunneling spectroscopies, *Surf. Sci.* **563**, 191 (2004).
5. C.H. Liu, I. Matsuda, R. Hobara, and S. Hasegawa, Interaction between adatom-induced localized states and a quasi-two-dimensional electron gas, *Phys. Rev. Lett.* **96**, 036803 (2006).
6. N. Sato, S. Takeda, T. Nagao, and S. Hasegawa, Electron standing waves on the Si(111)- √3×√3-Ag surface, *Phys. Rev. B* **59**, 2035 (1999).
7. N. Sato, T. Nagao, and S. Hasegawa, Two-dimensional adatom gas phase on the Si(111)- √3×√3-Ag surface directly observed by scanning tunneling microscopy, *Phys. Rev. B* **60**, 16083 (1999).
8. Y. Nakajima, S. Takeda, T. Nagao, S. Hasegawa, and X. Tong, Surface electrical conduction due to carrier doping into a surface-state band on Si(111) - √3×√3-Ag, *Phys. Rev. B* **56**, 6782 (1997).
9. S. Hasegawa and S. Ino, Surface structures and conductance at epitaxial growths of Ag and Au on the Si(111) surface, *Phys. Rev. Lett.* **68**, 1192 (1992).
10. S. Hasegawa, I. Shiraki, F. Tanabe, R. Hobara, T. Kanagawa, T. Tanikawa, I. Matsuda, C.L. Petersen, T.M. Hansen, P. Boggild, and F. Grey, Electrical conduction through surface superstructures measured by microscopic four-point probes, *Surf. Rev. Lett.* **10**, 963 (2003).
11. I. Shiraki, T. Nagao, S. Hasegawa, C.L. Petersen, P. Bøggild, T.M. Hansen, and F. Hansen, Micro-four-point probes in a UHV scanning electron microscope for *in-situ* surface-conductivity measurements, *Surf. Rev. Lett.* **7**, 533 (2000).
12. C.L. Petersen, F. Grey, I. Shiraki, and S. Hasegawa, Microfour-point probe for studying electronic transport through surface states, *Appl. Phys. Lett.* **77**, 3782 (2000).
13. S. Hasegawa, I. Shiraki, T. Tanikawa, C.L. Petersen, T.M. Hansen, P. Boggild, and F. Grey, Direct measurement of surface-state conductance by microscopic four-point probe method, *J. Phys. Condens. Matter* **14**, 8379 (2002).
14. T. Tanikawa, I. Matsuda, R. Hobara, and S. Hasegawa, Variable-temperature micro-four-point probe method for surface electrical conductivity measurements in ultrahigh vacuum, *e-J. Surf. Sci. Nanotech.* **1**, 50 (2003).
15. I. Shiraki, F. Tanabe, R. Hobara, T. Nagao, and S. Hasegawa, Independently driven four-tip probes for conductivity measurements in ultrahigh vacuum, *Surf. Sci.* **493**, 633 (2001).
16. S. Hasegawa, I. Shiraki, F. Tanabe, and R. Hobara, Transport at surface nanostructures measured by four-tip STM, *Curr. Appl. Phys.* **2**, 465 (2002).
17. T. Kanagawa, R. Hobara, I. Matsuda, T. Tanikawa, A. Natori, and S. Hasegawa, Anisotropy in conductance of a quasi-one-dimensional metallic surface state measured by a square micro-four-point probe method, *Phys. Rev. Lett.* **91**, 036805 (2003).
18. W. Norimatsu and M. Kusunoki, Transitional structures of the interface between graphene and 6H–SiC (0001), *Chem. Phys. Lett.* **468**, 52 (2009).
19. A. Bostwick, T. Ohta, T. Seyller, K. Horn, and E. Rotenberg, Quasiparticle dynamics in graphene, *Nat. Phys.* **3**, 36 (2007).
20. S. Ichinokura, K. Sugawara, A. Takayama, T. Takahashi, and S. Hasegawa, Superconducting calcium-intercalated bilayer graphene, *ACS*

E-mail: shuji@surface.phys.s.u-tokyo.ac.jp

Submitted: 25 November 2024; Accepted: 17 December 2024; Published Online: 28 February 2025

Nano **10**, 2761 (2016).

21. Y. Cao, V. Fatemi, S. Fang, K. Watanabe, T. Taniguchi, E. Kaxiras, and P.J. Herrero, Unconventional superconductivity in magic-angle graphene superlattices, *Nature* **556**, 43 (2018).
22. Y. Cao, V. Fatemi, A. Demir, S. Fang, S.L. Tomarken, J.Y. Luo, J.D.S. Yamagishi, K. Watanabe, T. Taniguchi, E. Kaxiras, R.C. Ashoori, and P.J. Herrero, Correlated insulator behaviour at half-filling in magic-angle graphene superlattices, *Nature* **556**, 80 (2018).
23. J.B. Goodenough and K.S. Park, The Li-ion rechargeable battery: a perspective, *J. Am. Chem. Soc.* **135**, 1167 (2013).
24. T.E. Weller, M. Ellerby, S.S. Saxena, R.P. Smith, and N.T. Skipper, Superconductivity in the intercalated graphite compounds C_6Yb and C_6Ca, *Nat. Phys.* **1**, 39 (2005).
25. Y. Endo, X. Yan, M. Li, R. Akiyama, C. Brandl, J.Z. Liu, R. Hobara, S. Hasegawa, W.S. Wan, K.S. Novoselov, and W.X. Tang, Dynamic topological domain walls driven by lithium intercalation in graphene, *Nat. Nanotechnol.* **18**, 1154 (2023).
26. W. Norimatsu and M. Kusunoki, Growth of graphene from SiC{0001} surfaces and its mechanisms, *Semicond. Sci. Technol.* **29**, 064009 (2014).
27. J.S. Alden, A.W. Tsen, P.Y. Huang, R. Hovden, L. Brown, J. Park, D.A. Muller, and P.L. McEuen, Strain solitons and topological defects in bilayer graphene, *Proc. Natl. Acad. Sci. U.S.A.* **110**, 11256 (2013).
28. N.M. Caffrey, L.I. Johansson, C. Xia, R. Armiento, I.A. Abrikosov, and C. Jacobi, Structural and electronic properties of Li-intercalated graphene on SiC(0001), *Phys. Rev. B* **93**, 195421 (2016).
29. M. Yamada, T. Hirahara, R. Hobara, S. Hasegawa, H. Mizuno, Y. Miyatake, and T. Nagamura, Surface electrical conductivity measurement system with micro-four-point probes at sub-kelvin temperature under high magnetic field in ultrahigh vacuum, *e-J. Surf. Sci. Nanotech.* **10**, 400 (2012).
30. H. Toyama, R. Akiyama, S. Ichinokura, M. Hashizume, T. Iimori, Y. Endo, R. Hobara, T. Matsui, K. Horii, S. Sato, T. Hirahara, F. Komori, and S. Hasegawa, Two-dimensional superconductivity of Ca-intercalated graphene on SiC: vital role of the interface between monolayer graphene and the substrate, *ACS Nano* **16**, 3582 (2022).
31. E. Belandria, Propiedades vibracionales de nanotubos de carbono de doble pared vacíos y rellenos con Se, Te, Fe, HgTe, PbTe, CdSe y PbI2 (Doctoral dissertation, Universidad de los Andes, Venezuela, 2008).
32. M. Orlita and M. Potemski, Dirac electronic states in graphene systems: optical spectroscopy studies, *Semicond. Sci. Technol.* **25**, 063001 (2010).
33. G. Csányi, P.B. Littlewood, A.H. Nevidomskyy, C.J. Pickard, and B.D. Simons, The role of the interlayer state in the electronic structure of superconducting graphite intercalated compounds, *Nat. Phys.* **1**, 42 (2005).
34. J.H. Dil, Spin and angle resolved photoemission on non-magnetic low-dimensional systems, *J. Phys. Condens. Matter* **21**, 403001 (2009).
35. 95th Birthday of Emmanuel Rashba, *J. Exp. Theor. Phys.* **135**, 387 (2022).
36. A.V. Matetskiy, S. Ichinokura, L.V. Bondarenko, A.Y. Tupchaya, D.V. Gruznev, A.V. Zotov, A.A. Saranin, R. Hobara, A. Takayama, and S. Hasegawa, Two-dimensional superconductor with a giant Rashba effect: one-atom-layer Tl-Pb compound on Si(111), *Phys. Rev. Lett.* **115**, 147003 (2015).
37. D.V. Gruznev, L.V. Bondarenko, A.V. Matetskiy, A.A. Yakovlev, A.Y. Tupchaya, S.V. Eremeev, E.V. Chulkov, J.P. Chou, C.M. Wei, M.Y. Lai, Y.L. Wang, A.V. Zotov, and A.A. Saranin, A strategy to create spin-split metallic bands on silicon using a dense alloy layer, *Sci. Rep.* **4**, 4742 (2014).
38. T. Nakamura, H. Kim, S. Ichinokura, A. Takayama, A.V. Zotov, A.A. Saranin, Y. Hasegawa, and S. Hasegawa, Unconventional superconductivity in the single-atom-layer alloy Si(111)− $\sqrt{3}\times\sqrt{3}$−(TlPb), *Phys. Rev. B* **98**, 134505 (2018).
39. H.J. Zhang, C.X. Liu, X.L. Qi, X. Dai, Z. Fang, and S.C. Zhang, Topological insulators in Bi_2Se_3, Bi_2Te_3 and Sb_2Te_3 with a single Dirac cone on the surface, *Nat. Phys.* **5**, 438 (2009).
40. S. Borisova, J. Krumrain, M. Luysberg, G. Mussler, and D. Grützmacher, Mode of growth of ultrathin topological insulator Bi_2Te_3 films on Si (111) substrates, *Cryst. Growth Des.* **12**, 6098 (2012).
41. A. Koma, Van der Waals epitaxy—a new epitaxial growth method for a highly lattice-mismatched system, *Thin Solid Films* **216**, 72 (1992).
42. Y. Sakamoto, T. Hirahara, H. Miyazaki, S. Kimura, and S. Hasegawa, Spectroscopic evidence of a topological quantum phase transition in ultrathin Bi_2Se_3 films, *Phys. Rev. B* **81**, 165432 (2010).
43. Y. Xia, D. Qian, D. Hsieh, L. Wray, A. Pal, H. Lin, A. Bansil, D. Grauer, Y.S. Hor, R.J. Cava, and M.Z. Hasan, Observation of a large-gap topological-insulator class with a single Dirac cone on the surface, *Nat. Phys.* **5**, 398 (2009).
44. T. Hirahara, Y. Sakamoto, Y. Takeichi, H. Miyazaki, S. Kimura, I. Matsuda, A. Kakizaki, and S. Hasegawa, Anomalous transport in an *n*-type topological insulator ultrathin Bi_2Se_3 film, *Phys. Rev. B* **82**, 155309 (2010).
45. M. Aitani, Y. Sakamoto, T. Hirahara, M. Yamada, H. Miyazaki, M. Matsunami, S. Kimura, and S. Hasegawa, Fermi-level tuning of topological insulator thin films, *Jpn. J. Appl. Phys.* **52**, 110112 (2013).
46. D. Fan, R. Hobara, R. Akiyama, and S. Hasegawa, Inverse spin Hall effect induced by asymmetric illumination of light in topological insulator Bi_2Se_3, *Phys. Rev. Research* **2**, 023055 (2020).
47. A.V. Matetskiy, I.A. Kibirev, A.N. Mihalyuk, S.V. Eremeev, D.V. Gruznev, L.V. Bondarenko, A.Y. Tupchaya, A.V. Zotov, and A.A. Saranin, Theory versus experiment for a family of single-layer compounds with a similar atomic arrangement: (Tl, *X*)/Si (111) $\sqrt{3}\times\sqrt{3}$ (*X*= Pb, Sn, Bi, Sb, Te, Se), *Phys. Rev. B* **96**, 085409 (2017).
48. T. Hirahara, S.V. Eremeev, T. Shirasawa, Y. Okuyama, T. Kubo, R. Nakanishi, R. Akiyama, A. Takayama, T. Hajiri, S. Ideta, M. Matsunami, K. Sumida, K. Miyamoto, Y. Takagi, K. Tanaka, T. Okuda, T. Yokoyama, S. Kimura, S. Hasegawa, and E.V. Chulkov, Large-gap magnetic topological heterostructure formed by subsurface incorporation of a ferromagnetic layer, *Nano Lett.* **17**, 3493 (2017).
49. T. Takashiro, R. Akiyama, I.A. Kibirev, A.V. Matetskiy, R. Nakanishi, S. Sato, T. Fukasawa, T. Sasaki, H. Toyama, K.L. Hiwatari, A.V. Zotov, A.A. Saranin, Toru Hirahara, and S. Hasegawa, Soft-magnetic skyrmions induced by surface-state coupling in an intrinsic ferromagnetic topological insulator sandwich structure, *Nano Lett.* **22**, 881 (2022).