



PLASMONS IN UNCONVENTIONAL SUPERCONDUCTIVITY AND TOPOLOGICAL QUANTUM SYSTEMS: FROM FESE-BASED SUPERCONDUCTORS TO TOPOLOGICAL INSULATOR HETEROSTRUCTURES

Zhongxiu Liu*, Qingjin Xu, Ling Zhao, Chengtao Wang, Yang Huang, Feiping Ning, Zhilong Hou, Rui Kang, Chunyan Li

Article Received on 20/08/2026

Article Revised on 10/09/2026

Article Published on 01/10/2026

*Corresponding Author

Zhongxiu Liu

<https://doi.org/10.5281/zenodo.23038109>



How to cite this Article: Zhongxiu Liu*, Qingjin Xu, Ling Zhao, Chengtao Wang, Yang Huang, Feiping Ning, Zhilong Hou, Rui Kang, Chunyan Li. (2026). Plasmons In Unconventional Superconductivity and Topological Quantum Systems: From Fese-Based Superconductors To Topological Insulator Heterostructures. World Journal of Engineering Research and Technology, 12(10), 85-95.

This work is licensed under Creative Commons Attribution 4.0 International license.

ABSTRACT

Plasmons, as collective oscillations of free electrons in solids, exhibit characteristics of both light and electrons, and demonstrate rich novel physical properties and functional application prospects in low-dimensional quantum systems. This article provides a systematic discussion of the role of plasmons in unconventional superconductivity and topological quantum materials. In the FeSe-based high-temperature superconducting system, we proposed an interfacial dynamical polaron model for the monolayer FeSe/SrTiO₃ system, clarifying that the oxide substrate enhances electron pairing within the FeSe layer through electron-phonon coupling. Furthermore, we established a polaron-bipolaron two-fluid model to explain the anomalous electrical transport

in (Li_{1-x}Fe_x)FeSe films, and proposed a "phonon + plasmon" multi-channel pairing mechanism, successfully explaining the non-monotonic evolution of T_c with carrier concentration in monolayer FeSe/STO, and predicting the isotope effect and plasmon-induced replica bands under multi-channel pairing. In topological quantum systems, we established an effective coupling model between topological surface states and two-dimensional electron gas, predicting gap opening in novel interband plasmons induced by band inversion and Dirac plasmons; two newly tunable plasmon modes were discovered in graphene/topological insulator heterostructures, and a novel probing approach based on

inverting the topology of the system through plasmon modes was proposed by analogy with the bulk-boundary correspondence. This article concludes with a summary of the limitations of the innovations and an outlook on the development directions of this field.

KEYWORDS: Plasmon; Unconventional superconductivity; FeSe-based superconductors; Polarons; Multi-channel pairing; Topological insulators; Heterostructures.

1 INTRODUCTION

1.1 Overview of Plasmons and Quantum Plasmons

Plasmons describe the collective oscillation of free electrons relative to ion cores in solids, and their excitation modes can be induced by light or high-energy electrons.^[1] In metals or on nanoparticle surfaces, plasmons exist as surface plasmons, which can focus incident light to subwavelength scales, enabling nanoscale manipulation of light^[2], with broad application prospects in photonics, sensing, and information circuits.^[3] With the rise of two-dimensional layered materials, low dimensionality and small size make the quantum confinement effects of the system significant, rendering classical electromagnetic field models inapplicable; such systems fall within the domain of quantum plasmons.^[4]

1.2 Overview of Research Techniques and Theoretical Method Advances

FeSe-based superconductors, due to their simplest structure and the sensitivity of superconducting transition temperature to carrier concentration, have become an ideal platform for understanding the mechanism of high-temperature superconductivity.^[5] Bulk FeSe has a T_c of only about 8 K^[6], but when monolayer FeSe is grown on SrTiO₃ substrate, T_c can increase dramatically, with in-situ angle-resolved photoemission spectroscopy observing clear replica bands and high transition temperature^[7], and scanning tunneling microscopy even reporting superconducting gap features exceeding 100 K.^[8] The microscopic mechanism of substrate enhancement of superconductivity charge transfer, interfacial phonons, or electronic correlations remains debated to this day.^[9]

Theoretically, conventional BCS and Migdal-Eliashberg theory is built on the adiabatic approximation, requiring phonon frequencies to be much lower than the Fermi energy.^[10] However, unconventional superconducting systems generally have low carrier concentration, with Fermi energy comparable to boson energy, placing the system in a non-adiabatic regime where traditional pseudocoulomb potential treatment fails.^[11] This opens space for plasmon participation in pairing: Takada proposed early on the plasmon-mediated superconducting

mechanism in two- and three-dimensional electron systems^[12], and Akashi and Arita further developed density functional theory for plasmon-assisted superconducting states.^[13] On the other hand, the experimental discovery of the quantum spin Hall effect and topological Dirac insulators opened the research of topological quantum states^[28], with Dirac cone surface states protected by time-reversal symmetry existing on the surface of three-dimensional topological insulators^{[14][29]}, and surface electron doping introducing a trivial two-dimensional electron gas.^[15] The spatial proximity of the two necessarily leads to coupling, providing a completely new band environment for surface plasmons.

2 Polarons and Plasmons in FeSe-Based Superconductors

2.1 Interfacial Dynamical Polarons in Monolayer FeSe/STO

In the monolayer FeSe/SrTiO₃ system, experiments have found that its collective excitations exhibit polaronic behavior: electrons carry polaron properties, where polarons are formed by electrons in the FeSe layer and the lattice distortion they induce in STO. Considering the non-adiabatic nature of the system ($E_a/\Omega_{ph} < 1$), we proposed a phenomenological model of interfacial dynamical polarons: the high-frequency longitudinal optical phonons of the substrate act as pairing glue, further strengthening the pairing strength of electrons in the FeSe layer through electron-phonon coupling. The effective Hamiltonian of polaron-phonon coupling can be written as

$$H_{p-ph} = \sum_{\mathbf{q}} g(\mathbf{q}) \rho_{\mathbf{q}} (b_{\mathbf{q}} + b_{-\mathbf{q}}^\dagger) \quad (1)$$

where $g(\mathbf{q})$ is the interfacial electron-phonon coupling strength, $\rho_{\mathbf{q}}$ is the FeSe layer electron density operator, and $b_{\mathbf{q}}$ is the substrate phonon annihilation operator. This model, beyond explaining charge transfer effects, quantitatively characterizes the enhancement contribution of substrate phonons to interfacial superconductivity.^[17] The effect of substrate charge doping on monolayer FeSe superconductivity has been independently calibrated by experiments^[31], and the theoretical picture of substrate interfacial soft phonons driving high-temperature superconductivity in monolayer FeSe is complementary to this^[32], jointly supporting the coexistence of phonon and charge two functions in the interfacial dynamical polaron model.

2.2 Polaron-Bipolaron Two-Fluid Model in (Li_{1-x}Fe_x)FeSe

Extending the polaron picture to bulk layered systems, a polaron-bipolaron two-fluid model was established in (Li_{1-x}Fe_x)FeSe films. When the electron-phonon coupling is sufficiently strong, two polarons can bind to form bipolarons, and the system simultaneously contains

two types of carriers — single polarons and bipolarons — whose transport properties are determined by the competition and conversion between the two fluids. This model successfully explains the experimentally observed "S"-shaped normal-state electrical transport curves, indirectly confirming that electron-phonon interaction is the primary glue source for electron pairing in this system.^[18] The binding energy of bipolarons can be estimated through variational methods, and their stability directly depends on the balance between Coulomb repulsion and lattice distortion energy. The surface electronic structure measurement of the isotropic superconducting gap in this film^[34] provides experimental basis for the determination of s-wave pairing under the polaron picture.

3 Phonon + Plasmon Multi-Channel Pairing Mechanism

3.1 Pairing Contribution of Low-Energy Plasmons

$$V_{\text{plas}}(\mathbf{k}, \mathbf{k}') = |V_{\text{eff}}(\mathbf{q})|^2 D(\mathbf{q}, \omega) \quad (2)$$

The electron-phonon picture alone is insufficient to explain all features of FeSe-based superconductors, especially the sensitive dependence of T_c on carrier concentration — rising from 8 K in bulk to approximately 40 K through electron doping.^[6] We found that the energy of low-energy plasmons in the monolayer FeSe/STO system is comparable to phonon energy, and the pairing coherence length induced by plasmons is close to that induced by phonons, so the two can cooperatively enhance electron pairing strength. The effective interaction under multi-channel pairing is

$$V_{\text{eff}} = V_{\text{ph}} + V_{\text{plas}} \quad (3)$$

where V_{ph} and V_{plas} are the attractive interactions of the phonon and plasmon channels, respectively. In non-adiabatic systems, the treatment of the traditional pseudocoulomb potential μ^* fails, and the existence of low-energy plasmon modes greatly weakens Coulomb repulsion, significantly reducing the effective repulsive potential μ^*_{eff} . Consequently, the effective pairing strength of the system can be approximately expressed as the sum of the two-channel coupling constants

$$\lambda_{\text{eff}} = \lambda_{\text{ph}} + \lambda_{\text{plas}} \quad (4)$$

3.2 Explanation of T_c -Carrier Concentration Relation and Isotope Effect

The phonon + plasmon two-channel mechanism can naturally explain the variation of T_c with carrier concentration in the monolayer FeSe/STO system: at low carrier concentration, the system is in the non-adiabatic regime with significant polaron effects; the plasmon channel

strengthens with doping while the phonon channel remains relatively stable, and their synergy causes T_c to rise; upon further increasing doping, the Fermi energy rises and the system tends toward the adiabatic regime, the plasmon contribution weakens, and T_c decreases, thereby reproducing the dome-shaped phase diagram observed experimentally.^[19] The BCS-BEC crossover behavior exhibited by bulk FeSe under magnetic field provides independent corroboration for this carrier-concentration-driven pairing strength evolution.^[33] Furthermore, the two-channel mechanism predicts an anomalous isotope coefficient between 0 and 0.5, and predicts the plasmon-induced replica band phenomenon: in addition to the main band and phonon replica bands in ARPES spectra, an additional replica band whose spacing is determined by the plasmon energy should appear at higher binding energy, providing a directly testable experimental criterion for the multi-channel pairing mechanism.^[20] It is worth emphasizing that the prerequisite for low-energy plasmon contribution to superconductivity is the non-adiabatic mechanism caused by low carrier concentration, a prerequisite that commonly exists in unconventional superconducting systems such as FeSe-based, cuprate, alkali-metal-doped fullerenes, and twisted graphene.^[21]

4 Novel Plasmons in Topological Quantum Systems

4.1 Coupling of Topological Surface States and Two-Dimensional Electron Gas

$$H_{\text{coupling}} = \sum_{\{k, k'\}} V(k, k') c_{\{k, \text{TS}\}}^\dagger c_{\{k', 2\text{DEG}\}} + \text{h.c.} \quad (5)$$

Three-dimensional topological insulators such as Bi_2Se_3 possess a single Dirac cone surface state^[14], while intrinsic impurities or artificial surface electron doping introduce a two-dimensional electron gas near the surface due to band bending.^[15] Considering the close spatial proximity of the two, coupling necessarily occurs. Taking Bi_2Se_3 as an example, the effective coupling Hamiltonian between the topological surface state and the trivial two-dimensional electron gas is

After coupling, the topological nature of the topological surface state itself remains unaffected, but the topology can be "shared" with the originally trivial two-dimensional electron gas through the proximity effect, opening the spin-degenerate states to form Rashba-split states.^[22] The physical content of this surface state coupling has been comprehensively discussed in systematic reviews of topological insulators and superconductors.^[30]

4.2 Interband Plasmons and Dirac Plasmon Gap

$$\omega_{\text{pl}}(k) \propto \sqrt{k} \quad (6)$$

Based on the coupled single-particle ground state, band inversion greatly enhances the lifetime of interband electron-hole pairs, leading to the appearance of a new interband optical branch plasmon mode.^[16] Meanwhile, the previously widely studied Dirac plasmons acquire a gap due to the opening of additional interband dissipation channels. The dispersion of two-dimensional Dirac plasmons satisfies the square root law where the plasmon velocity is jointly determined by the Fermi velocity and the dielectric environment, and undergoes significant changes with the type of doped carriers (electrons or holes).^[23] In topological insulator thin films, the coupling of upper and lower surface plasmons also leads to mode splitting, forming symmetric and antisymmetric plasmon branches.^[24]

4.3 Plasmons in Graphene/Topological Insulator Heterostructures

Both graphene and topological insulators have attracted considerable attention due to their Dirac-type electronic dispersion, and heterostructures composed of the two can acquire novel properties through mutual proximity effects.^[25] First-principles calculations have found that after hybridization coupling between the graphene Dirac bands and the topological insulator upper surface states, two characteristic bands crossing the Fermi level are formed — a (mexican-hat-shaped) band and a bell-shaped band. After constructing a low-energy effective Hamiltonian to fit the bands near the Fermi level, it was found that the two plasmon modes respectively originate from the contributions of these two characteristic bands, while the remaining bands only provide additional interband electron-hole dissipation channels.^[4] By doping different types and concentrations of carriers, active selection of plasmon modes can be achieved in this system, providing guidance for applications of graphene/topological insulator heterostructures in optical devices.

4.4 Plasmons as Probes of Topology

The above novel plasmon modes are inextricably linked to topological surface states: the disappearance of surface states means the disappearance of corresponding plasmon modes. By analogy with the well-known bulk-boundary correspondence in topological insulators, experiments can verify the existence of surface states by measuring the plasmon modes corresponding to surface states — that is, using plasmon spectroscopy as a non-destructive probe of system topology.^[16] This approach is consistent with the research direction of determining non-trivial band topology in emerging topological quantum materials such as kagome superconductors through spectroscopic methods^[26]; and thermodynamic evidence for nematic superconductivity in doped topological insulator $\text{Cu}_x\text{Bi}_2\text{Se}_3$ also indicates that

symmetry-breaking collective behavior can similarly be cross-confirmed through thermodynamic and spectroscopic methods.^[35]

5 Limitations of Innovations and Future Directions

5.1 Main Innovations

First, the interfacial dynamical polaron model for monolayer FeSe/STO was proposed, unifying the pairing glue function of substrate phonons with polaron physics^[17]; second, the polaron-bipolaron two-fluid model was established, explaining the anomalous electrical transport in $(\text{Li}_{1-x}\text{Fe}_x)\text{FeSe}$ ^[18]; third, the phonon + plasmon multi-channel pairing mechanism was proposed, explaining the T_c -carrier concentration dome and predicting anomalous isotope effects and plasmon replica bands; fourth, interband plasmons and Dirac plasmon gaps induced by coupling of topological surface states and two-dimensional electron gas were predicted; fifth, the probing principle of inverting system topology through plasmon modes was proposed, extending the experimental connotation of bulk-boundary correspondence.

5.2 Existing Limitations

The existing work still has limitations. The plasmon spectral functions in the multi-channel pairing model are mostly taken from RPA approximation, with insufficient characterization of local field effects in strongly correlated systems; the parameters of the polaron picture rely on a combination of first-principles calculations and experimental fitting, lacking independent determination methods; the predicted plasmon replica bands and anomalous isotope effects still await direct verification by high-resolution ARPES and isotope substitution experiments; calculations of plasmons in topological systems are mostly based on low-energy effective models, with insufficient inclusion of real material band details, impurity scattering, and temperature effects.^[23]

5.3 Future Directions

Future directions include: developing multi-channel Eliashberg theory in the non-adiabatic limit, incorporating phonons, plasmons, and spin fluctuations into a unified self-consistent framework^[13]; directly observing interfacial plasmon modes and their correlation with superconducting gaps using high-resolution EELS and near-field optical microscopy techniques; extending the multi-channel pairing picture to emerging low-carrier-concentration systems such as twisted graphene and nickel-based superconductors; and exploring applications of actively selectable plasmon modes in graphene/topological insulator heterostructures in terahertz modulators and quantum sensing devices.

6 Summary and Outlook on Broad Field Directions

Starting from solid quasiparticles — plasmons — this article summarizes their properties and applications in unconventional superconductivity and topological quantum systems along two main threads. Regarding superconducting pairing mechanisms, the interfacial dynamical polaron model and the phonon + plasmon multi-channel mechanism provide self-consistent explanations for core experimental features of FeSe-based superconductors, including substrate enhancement and the T_c -carrier concentration dome^[19], and yield two testable predictions: the isotope effect and replica bands. In topological quantum systems, the coupling of topological surface states and two-dimensional electron gas produces novel collective excitations such as interband plasmons, and the tunable plasmon modes in graphene/topological insulator heterostructures provide a design blueprint for nanophotonic devices.

From the perspective of broad field directions, the resolution of the high-temperature superconducting pairing mechanism still faces dual bottlenecks: experimentally, there is a lack of conclusive evidence — the order parameter symmetry of monolayer FeSe/STO remains disputed across different measurements^[20]; theoretically, no tool can rigorously treat strong correlation effects, and existing microscopic and phenomenological theories all rely on system-specific approximations.^[11] What is urgently needed at present is innovation in experimental techniques and theoretical methods: on one hand, developing in-situ, non-destructive, energy-momentum fully resolved spectroscopic methods; on the other hand, establishing a universal theoretical framework that can simultaneously accommodate electron-phonon coupling, Coulomb correlations, and collective mode feedback. With the emergence of new platforms such as twisted graphene^[21], topological superconductor candidates^[27], and kagome superconductors^[26], plasmons, as a bridge connecting many-body physics, topological quantum theory, and nanophotonic applications, will undoubtedly play an increasingly crucial role on both fronts of high-temperature superconducting mechanism and topological quantum information.

Declarations

Funding

The authors did not receive any specific funding for this work. No funds, grants, or other support were received from any organization for the submitted manuscript.

Conflict of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability Statement

The datasets generated and/or analysed during the current study are included in this article and its Supplementary Material (if any). Additional data supporting the findings of the study are available from the corresponding author upon reasonable request.

REFERENCES

1. Pines D, Bohm D. A collective description of electron interactions II: Collective vs individual particle aspects of the interactions [J]. *Phys Rev.*, 1952; 85(2): 338-350.
2. Maier S A. *Plasmonics: Fundamentals and Applications* [M]. New York: Springer Science+Business Media, 2007.
3. Barnes W L, Dereux A, Ebbesen T W. Surface plasmon subwavelength optics [J]. *Nature*, 2003; 424(6950): 824-830.
4. Hwang E H, Das Sarma S. Dielectric function, screening, and plasmons in two-dimensional graphene [J]. *Phys Rev B.*, 2007; 75(20): 205418.
5. Hsu F-C, Luo J-Y, Yeh K-W, et al. Superconductivity in the PbO-type structure α -FeSe [J]. *Proc Natl Acad Sci USA*, 2008; 105(38): 14262-14264.
6. Wang Q Y, Li Z, Zhang W H, et al. Interface-induced high-temperature superconductivity in single unit-cell FeSe films on SrTiO₃ [J]. *Chin Phys Lett*, 2012; 29(3): 037402.
7. He S, He J, Zhang W, et al. Phase diagram and electronic indication of high-temperature superconductivity at 65 K in single-layer FeSe films [J]. *Nat Mater*, 2013; 12(7): 605-610.
8. Ge J F, Liu Z L, Liu C, et al. Superconductivity above 100 K in single-layer FeSe films on doped SrTiO₃ [J]. *Nat Mater*, 2015; 14(3): 285-289.
9. Lee D Lee. Routes to high-temperature superconductivity: A lesson from FeSe/SrTiO₃ [J]. *Annu Rev Condens Matter Phys*, 2018; 9(1): 261-282.
10. Migdal A B. Interaction between electrons and the lattice vibrations in a normal metal [J]. *Sov Phys JETP*, 1958; 7(6): 996-1001.
11. Morel P, Anderson P W. Calculation of the superconducting state parameters with retarded electron-phonon interaction [J]. *Phys Rev.*, 1962; 125(4): 1263-1271.
12. Takada Y. Plasmon mechanism of superconductivity in two- and three-dimensional electron systems [J]. *J Phys Soc Jpn.*, 1978; 45(3): 786-794.

13. Akashi R, Arita R. Development of density-functional theory for a plasmon-assisted superconducting state: Application to lithium under high pressures [J]. *Phys Rev Lett.*, 2013; 111(5): 057006.
14. Zhang H, Liu C-X, Qi X-L, et al. Topological insulators in Bi₂Se₃, Bi₂Te₃ and Sb₂Te₃ with a single Dirac cone on the surface [J]. *Nat Phys.*, 2009; 5(6): 438-442.
15. Bianchi M, Guan D, Bao S, et al. Coexistence of the topological state and a two-dimensional electron gas on the surface of Bi₂Se₃ [J]. *Nat Commun*, 2010; 1: 128.
16. Politano A, Silkin V M, Nechaev I A, et al. Interplay of surface and Dirac plasmons in topological insulators: The case of Bi₂Se₃ [J]. *Phys Rev Lett.*, 2015; 115(21): 216802.
17. Huang D, Hoffman J E. Monolayer FeSe on SrTiO₃ [J]. *Annu Rev Condens Matter Phys.*, 2017; 8: 311-336.
18. Alexandrov A S, Mott N F. *Polarons and Bipolarons* [M]. Singapore: World Scientific, 1995.
19. Zhang S, Miao G, Guan J, et al. Superconductivity of the FeSe/SrTiO₃ interface in view of BCS-BEC crossover [J]. *Chin Phys Lett.*, 2019; 36(10): 107404.
20. Fan Q, Zhang W, Liu X, et al. Plain s-wave superconductivity in single-layer FeSe on SrTiO₃ probed by scanning tunnelling microscopy [J]. *Nat Phys.*, 2015; 11(11): 946-952.
21. Cao Y, Fatemi V, Fang S, et al. Unconventional superconductivity in magic-angle graphene superlattices [J]. *Nature*, 2018; 556(7699): 43-50.
22. Zhu Z H, Levy G, Ludbrook B, et al. Rashba spin-splitting control at the surface of the topological insulator Bi₂Se₃ [J]. *Phys Rev Lett.*, 2011; 107(18): 186405.
23. Li X, Xiao D, Zhang Z. Landau damping of quantum plasmons in metal nanostructures [J]. *New J Phys.*, 2013; 15(2): 023011.
24. Profumo R E V, Asgari R, Polini M, et al. Double-layer graphene and topological insulator thin-film plasmons [J]. *Phys Rev B.*, 2012; 85(8): 085443.
25. Shan W Y, Lu H Z, Shen S Q. Effective continuous model for surface states and thin films of three-dimensional topological insulators [J]. *New J Phys.*, 2010; 12(4): 043048.
26. Ortiz B R, Teicher S M L, Hu Y, et al. CsV₃Sb₅: A Z₂ topological kagome metal with a superconducting ground state [J]. *Phys Rev Lett.*, 2020; 125(24): 247002.
27. Ran S, Eckberg C, Ding Q-P, et al. Nearly ferromagnetic spin-triplet superconductivity [J]. *Science*, 2019; 365(6454): 684-687.
28. Hsieh D, Qian D, Wray L, et al. A topological Dirac insulator in a quantum spin Hall phase [J]. *Nature*, 2008; 452(7190): 970-974.

29. Hasan M Z, Kane C L. Colloquium: Topological insulators [J]. *Rev Mod Phys.*, 2010; 82(4): 3045-3067.
30. Qi X-L, Zhang S-C. Topological insulators and superconductors [J]. *Rev Mod Phys.*, 2011; 83(4): 1057-1110.
31. Zhang W, Li Z, Li F, et al. Interface charge doping effects on superconductivity of single-unit-cell FeSe films on SrTiO₃ substrates [J]. *Phys Rev B.*, 2014; 89(6): 060506.
32. Rosenstein B, Shapiro B Y. High-temperature superconductivity in single unit cell layer FeSe due to soft phonons in the interface layer of the SrTiO₃ substrate [J]. *Phys Rev B*, 2017; 95(22): 220504.
33. Kasahara S, Watashige T, Hanaguri T, et al. Field-induced superconducting phase of FeSe in the BCS-BEC crossover [J]. *Proc Natl Acad Sci USA*, 2016; 113(46): 13051-13055.
34. Niu X H, Peng R, Xu H C, et al. Surface electronic structure and isotropic superconducting gap in (Li_{0.8}Fe_{0.2})OHFeSe films [J/OL]. *Adv Mater*, 2018.
35. Yonezawa S, Tajiri K, Nakata S, et al. Thermodynamic evidence for nematic superconductivity in Cu_xBi₂Se₃ [J]. *Nat Phys.*, 2017; 13(2): 123-126.