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Condensed Matter Physics: From understanding to originality

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ABSTRACT

The field of "Condensed Matter Physics (CMP)" investigates how the interactions of many atoms and electrons give rise to the basic features of the matter. Because of the complexity of these interactions, the resulting characteristics and occurrences frequently suggest a deep insight of physics. While new findings are continuously shifting the focus, the fundamental difficulties in CMP remain the same: to anticipate and witness unexpected occurrences and to describe unique features of materials, many of which are at the cutting edge of quantum mechanics.

Keywords: ***Condensed, Matter, Physics, Quantum, Mechanics***

INTRODUCTION

When it comes to stimulating technical innovation, CMP is likewise in the forefront. For well over half a century, the semiconductor industry has been the primary catalyst for CMP's continued development[1]. The semiconductor industry may thank pioneering scientists for the transistor, a fundamental component of today's electronic products. Moore's law [2] describes the exponential growth in computing power that has occurred since the introduction of the transistor. The versatility of CMP [3] is due to the constant interaction between the underlying science and technology applications.

Condensed matter and materials physics is now interested in a broad range of CMP issues, but it is hard to give them all due here. Instead of trying to cover everything, this essay will focus on a few key issues whose resolution would significantly advance our understanding and knowledge, as well as on some emerging functional properties of materials, the applications of which have the potential to spur technological innovation. Astonishing phenomena in condensed matter arise from interactions between particles and the interplay between connected degrees of freedom. Due to their quantum mechanical character, the events seen in condensed matter are often non-trivial and defy common sense. One of the most remarkable manifestations of this kind of behaviour is superconductivity.

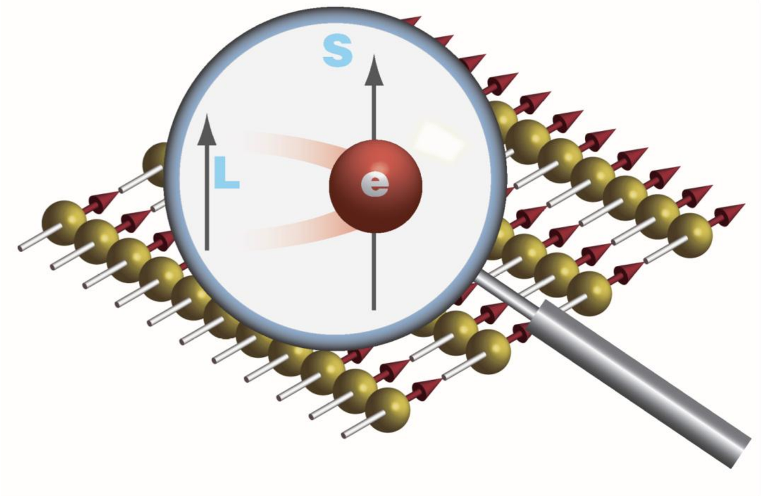


Fig 1:CMP of energy matter

What makes a material "superconducting" is its ability to transport an electric current without losing any of that energy to heat or friction. When Onnes first saw it in 1911, no one knew what caused it [4]. In metals when the superconducting transition occurs at cryogenic temperatures, the BCS theory offered a coherent explanation for this phenomena. “Twenty years later, however, cuprate superconductors were found by Karl Müller and Johannes Bednorz [5]. The electron-phonon interaction explains why these high-temperature superconductors don't fit the BCS theory, which is based on electron pairing. The finding of superconductivity in iron pnictides may provide a non-conventional route for high-temperature superconductivity. CMP struggles to comprehend superconductivity's tiny nature” in these materials.

Understanding strongly “correlated electrical systems helps solve CMP's high-temperature superconductivity dilemma. Highly linked systems have electrical activity that cannot be understood without particle interaction. In doped complex oxide materials, a tightly connected many-body ground state may form when valence electron interaction energy exceeds kinetic energy. Localized f levels hybridised with s, p, and d states make it challenging to approximate the strong on-site and inter-site Coulomb interactions in actinides and lanthanides using a single-particle wave function. Competition between electronic phases, which have differing charge and spin ordering and length and energy scales, controls high-correlated systems' characteristics. This rivalry causes intricate phase diagrams and inherent inhomogeneitiesun many materials (such phase separation). Strong electron-electron correlations make these materials susceptible to environmental perturbations, leading in intriguing behaviours including high-temperature superconductivity, huge magneto resistance, metal-insulator transitions, and more. The quantum mechanical single particle description (with many perturbations and corrections) may describe a remarkable amount of condensed matter events, but the solutions are generally ad hoc and only tangentially address the many body electronic structure.” One of CMP's greatest challenges is rethinking solid-state theory so that it can capture the complexities of highly coupled systems.

Emergence of non-trivial cooperative phenomena

While the interaction between well-known components generally drives the creation of non-trivial cooperative events in CMP, the collective behaviour may be startlingly diverse and often surprising. Indeed, this holds true for the newly discovered quantum states of matter. A peculiar electronic liquid is the fractional quantum Hall state [6, 7], in which a dissociated extra electron splits into particles that each carry an exact proportion of the original electron's charge. In a two-dimensional electron system, a perpendicular magnetic field causes a collection of discontinuous states known as Landau levels. If the magnetic field is strong enough, all electrons will settle to the same rest velocity on the ground Landau level. Electrons are a new strongly-correlated form of matter in which the Coulomb contact between them dominates their activity.

The study of critical phenomena and phase transitions is an integral part of contemporary critical material science. The term "phase transition" describes the change from one phase or condition of matter in a thermodynamic system to another. Systems undergoing a phase transition often display divergent properties, such as specific heat and susceptibility, close to the critical point. This system exhibits unusual critical behaviour close to the critical temperature, where it is difficult to classify the state as belonging to either of the two phases involved in the transition. The phase change from paramagnetic to ferromagnetic is one example of this. The so-called mean field approximation is used by the Ginzburg-Landau theory [8] to provide an explanation for continuous phase transitions. While the Ginzburg-Landau model is generally applicable, there are exceptions, such as the metal-insulator phase transition. Studies of phase transitions, especially those involving closely coupled systems, are now under investigation.

When it comes to the intricacy of physical processes, look no farther than the existence of soft matter, a subset of condensed matter characterised by physical states that are easily deformed by thermal or mechanical forces. Soft matter consists of a wide variety of organic components, including polymers, colloids, and liquid crystals. Soft matter's most fascinating properties stem from its atomic or molecular components, a feature shared by many materials. The complex and varied physical behaviours of soft matter may be traced back to interactions occurring at the mesoscopic scale, which includes a significant number of atoms and molecules yet is considerably smaller than the macroscopic size. Despite their diversity, soft materials have common characteristics such as several degrees of freedom, weak interactions between structural parts, and a careful balance between entropy and enthalpy contributions to the free energy. In addition to being highly responsive to environmental cues, each of these materials also exhibits large temperature fluctuations, the formation of metastable states, and a remarkable degree of morphological diversity.

The investigation of nanoscale material characteristics is at the heart of a number of important ongoing CMP projects. Differences in material properties at scales of 100 nanometers or smaller from the bulk properties give rise to novel phenomena and functional qualities. When things go down to the nanoscale, surface and interface qualities become more important than bulk features: "The interface is the device," as Kroemer puts it. Somehow, the traditional concept that Wolfgang Pauli espoused, that "God formed the mass; the surface was fashioned by the devil," has to be dismantled in CMP's society.

Several important features (conductivity, spin-orbit coupling, spin current) are shielded in certain systems due to their topology. These include topological insulators, which have a band gap in the bulk but conductivity at the surface or edge [10]. While band insulators may also contain conductive surface states [11, 12], the surface states of topological insulators are uniquely shielded by time reversal symmetry. Due to the quantized charge and spin conductance, the two-dimensional topological insulator may be seen as a quantum spin Hall state [13]. In this state, the spin and momentum of the carriers are linked through helical edge states. The observation of the quantum spin Hall effect in HgTe/(Hg,Cd)Te quantum wells [14] may be indicative of the existence of a new quantum state of matter. The skyrmion [15] is an example of a topological phenomenon in condensed matter; it is a twisted vertex configuration of a two-dimensional ferromagnet that has been studied extensively in other contexts for decades. Naturally occurring skyrmions may emerge in magnetic materials through the Dzyaloshinskii-Moriya interaction [16], without the need for defects or the application of external fields. Magnetic skyrmions typically have a size of 1 nm and organise into 2D lattices [17]. They may be valuable in information storage because to their ability to be created and destroyed with great precision utilising local spin-polarized currents from a scanning tunnelling microscope [18].

Fundamental studies in CMP

Fundamental investigations in CMP stimulate the discovery of new phenomena and materials features, which are typically realised in industrial advancements. We've already spoken about how the advent of the transistor revolutionised the semiconductor industry. Spintronics, in which the charge and spin of electrons are exploited to increase the performance of electrical and data storage devices [19], is another well-known one (but not as broad as semiconductor technology).

Exciting “spintronics include spin injection in metals and semiconductors, spin-dependent thermal effects, and current-driven spin-transfer torques. Given that spin transfer torques may be used to reverse the magnetization, they provide a powerful tool for programming MRAMs. This makes them very relevant to modern applications. In spite of the fact that the spin Hall effect was predicted over 40 years ago [25], it was only recently experimentally confirmed [26]. This phenomena may eventually be required for proper gadget operation. As a result of the spin-orbit interaction, an electric current induces a transverse spin current in a current-carrying material, leading to a spin accumulation on the lateral surfaces of the material. The spin current caused by the spin Hall effect offers fascinating possibilities for room-temperature spin-torque switching of magnetization in ferromagnets.

Emerging phenomena in CMP will likely play a determining role in extending or altering the shape of the International Technology Roadmap for Semiconductors [12] in order to maintain Moore's law in force. Source-drain leakage and, by extension, power dissipation, are both expanding at an alarming pace as the size of CMOS transistors is decreased to allow for higher speeds and greater packing densities. This problem can't be addressed without exploring novel materials and approaches to gadget operation. Other methods, such as voltage-controlled magnetization, graphene field-effect transistors, non-local spin-valve devices, and ferroelectric tunnel junctions, have also been proposed. To emphasise the non-volatile operation of these devices, a renewed focus on ferromagnetism and ferroelectricity, two long-standing key subfields of CMP, is being undertaken. Despite the challenges inherent in their pursuit, non-volatile memory and logic with switching energy of less than 102 fJ, switching speeds” of 1 GHz .

CMP is crucial to satisfying the energy needs of today's society. The widespread availability of cheap energy, mostly from fossil fuels, has facilitated scientific and societal progress. However, the worsening energy situation calls for concerted action to tap into renewable energy sources in order to develop greener, more efficient technology. To solve the current and future big problems of energy production, conversion, storage, and efficient consumption, the discovery of novel materials is essential. You can't overstate the importance of CMP in overcoming these difficulties [13].

The development of cheaper and more efficient solar cells, which use the photovoltaic effect to transform light energy into electricity, is one such example. Solid-state lighting is another area that has seen tremendous development in recent times. CMP has made and will continue to make important contributions to a number of other energy-related technologies. Some examples are photocatalytic direct solar power to hydrogen production by light-assisted water breakdown, and the creation of thermoelectric materials that may be utilised to convert thermal energy to electrical energy.

Density of states in low dimensions

The density of states function, which identifies how many potential energy levels exist in a system, is useful for calculating carrier concentrations and energy distributions inside a semiconductor. In semiconductors, the carriers can only travel along the x, y, and z axes.

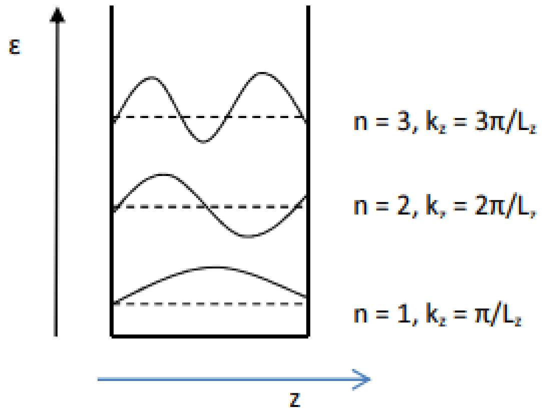
As the one-dimensional size of a structure (device) approaches an equivalence with important parameters, the low dimensionality of the system will influence the behaviour of the charge carriers. Excitons in semiconductors are often thought to have a size equal to the Bohr radius.

Bohr radius:

$$a_B = \frac{4\pi\hbar^2\varepsilon_0}{m_e e^2} = 5.3 \times 10^{-11} \text{ m (or 0.53 Å)},$$

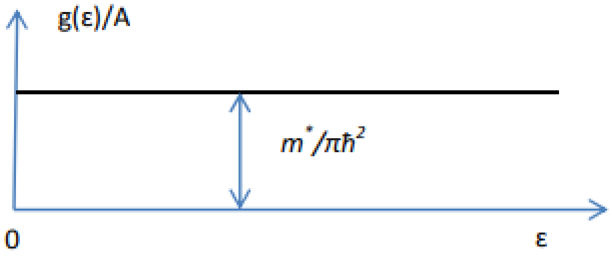
Electron states in confined structures:

In order to better understand the behaviour of charge carriers and, by extension, the macroscopic features (conductivity, band gaps, mobility, charge carrier concentration, etc.) crucial to the device applications, electron band structure diagrams are a valuable and instructive tool. Consequently, we will consider how quantum confinement modifies the electrical structure of materials in the next section. First, we will discuss the directionally-confined behaviour of electrons in a quantum well. The potential energy levels in the constrained directions are established by the boundary constraints imposed on the electron wave function by the structure. For the purpose of discussion, we will assume that the electron is travelling in a potential that is constant inside the structure and that there is an infinite potential barrier on each side of the electron. In this case, the over-barrier wave function is always zero.

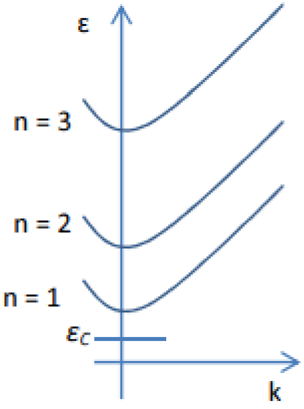


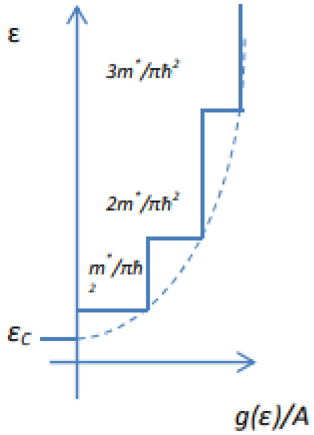
For a quantum well we will have for two dimensions where the movement is not restricted:

$$g(|k|) = \frac{A}{(2\pi)^2} 2\pi|k| \text{ and } g(\varepsilon) = \frac{A}{(2\pi)^2} 2\pi \sqrt{\frac{2m^*\varepsilon}{\hbar^2}} \sqrt{\frac{m^*}{2\hbar^2}}\, \varepsilon^{-1/2} \times 2 = \frac{Am^*}{\pi\hbar^2}$$



Now if we factor in the possible states in a potential well, then for the bottom of the conduction band we get:





It is impossible for the bulk semiconductor to have states at the valence band's lowest energy level. The density of states grows in distinct increments when the energy is raised. Similar to how the bulk band gap is bigger than the effective band gap, this is also true for the valence band when holes are present.

CONCLUSION

Even though the above instances are not exhaustive, they should give you a sense of the CMP study's breadth and depth. There is potential in the future for the discovery of innovative materials to reach ever-increasing functionality and performance. There is a glimmer of new data that calls us to a deeper knowledge of not just CMP but also other fields, like quantum mechanics in general, with respect to the fundamental issues, such providing a satisfactory description of highly coupled electronic systems. Additionally, key early universe cosmological phenomena are analogous to those seen in condensed matter, such as the emergence of topological defects or the occurrence of symmetry-breaking phase transitions. The widespread relevance of CMP to other academic fields serves to highlight both its significance and the intensity of its most pressing concerns.

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