強電場物理：非線形伝導とレーザー物理の境界

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雑然としていますが、強電場の物理についてまとめてみました。コメントや議論をお願いしたいと思います。

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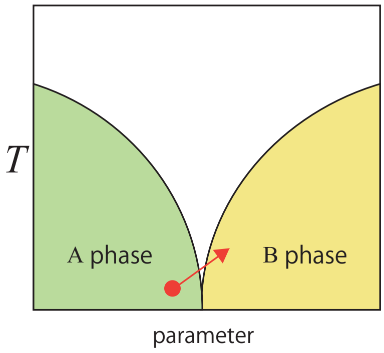

FIG. 1: Phase transition near two phases. In the case of a field induced nonequilibrium phase transitions, the "parameter" corresponds to the strength of the electric field and one aims to change the phase to a new "B" phase. Heating is always present making the arrow point upward.

Electron systems in strong electric fields provides many fundamental problems in nonequilibrium physics. While the interaction quench was aimed to study the relaxation mechanism, systems driven by strong electric fields casts many new and important questions. Perhaps, one of the most important physical questions is, *can we control a macroscopic many-body state in a quantum coherent manner?* Naturally, this is a difficult question with no concrete answer yet. Coherent motion of electrons can be easily destroyed in the presence of electron-electron scattering since the momentum conservation is violated in lattice systems due to the Umklapp process. The study of Bloch oscillation reveals this clearly where the oscillation is damped quickly [24]. However, there is a way to utilize the largeness of the degrees of freedom, and to obtain huge output from very small input stimulus. The key is phase transition. When phase transitions occur, macroscopic number of electrons change their state in a coherent manner, leading to extremely large responses compared to stimulating each electrons individually. Many-body effects, as well as, topological mechanisms can triggle such phase transitions. In equilibrium, collosal magneto-registance in manganite systems is probably the most famous example for the former mechanism [32]. In the phase diagram of these systems, a charge ordered insulating phase neighbors a ferromagnetic metal. By applying magnetic field to the insulating state, one can metallize the system and the conductivity changes by several magnitudes. In general, applying stimulus to systems near the phase boundary, one can obtain large reponses [Fig. 1]. Recently, researchers are becoming interested in using strong electric fields to perform this task.

From the experimental side, there are two main ways to study the effect of electric field in solids. One is to perform a traditional nonlinear transport measurement by attaching electrodes to the sample [30]. Nonlinear transport in correlated electron system is a hot field and many interesting phenomena has been reported. To name a few, colossal electroresistance, i.e., large memory effect in the IV-characteristics [3, 18, 26, 28], thyristor effect, i.e., emergence of current oscillation [29], have been observed. Negative differential resistivity is seen in many correlated insulators [9, 19, 30]. It is often very difficult to identify the driving mechanisms in a nonlinear transport experiment because many factors must be considered. For example, the interface between the sample and electrode hosts several relevant effects such as oxygen migration, interface Mott transtion [25] and filament formation of conducting pathes [27]. Also strong Joule heating is present, which can explain some experiments on negative differential resistivity [1, 9, 19].

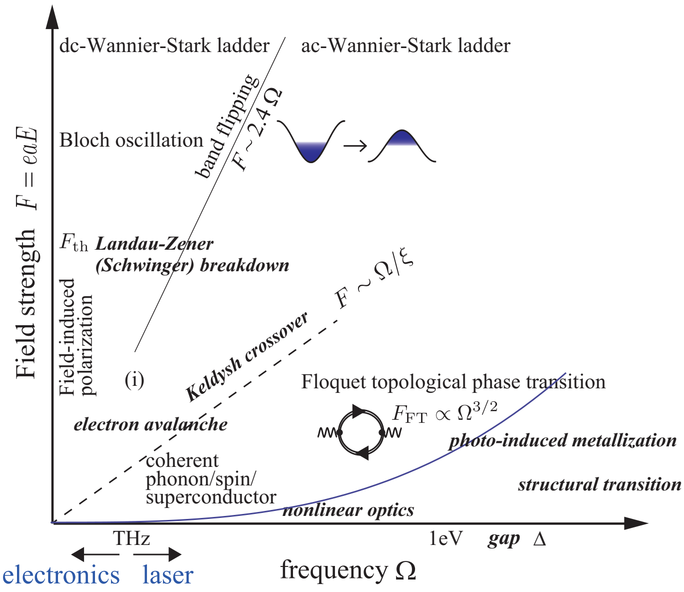

FIG. 2: Strong field physics in condensed matter: Various electric field induced phenomena plotted in the (F, Ω) space. Italic letters are specific to gapped systems. (i) corresponds to recent THz laser [6, 34].

The second method, free from interface effects, is to use strong laser. In Fig. 2, we show various laser indcued phenomena in the diagram of field strength F and photon energy Ω.

Photo-induced phase transition Nonequlibrium phase transition obtained by applying laser with photon energy larger than the gap is called photo-induced phase transition and is the most widely studied electric field effect (see [20, 33, 36] for reviews). In some materials, one can induce structural change in the lattice [4, 35]. Other are purely electronic, where a Mott insulator can be turned metallic [10], or ferromagnetic order can be photo-induced in manganites [31]. In some drastic cases, the emergent phase can be a “hidden” phase which do not exist in the equilibrium phase diagram[8]. Since the output of nonequilibrium phase transition can be large, it is expected that these phenomena can lead to novel devices such as all optical memory. See **??** for further information.

Electron avalanche One of the most important mechanism of dielectric breakdown of insulators in strong electric fields is the electron avalanche effect. Thermal electrons are accelerated in electric fields and when their kinetic energy exceeds the pair creation energy (gap), they can release the energy to create carriers. This was demonstrated in semiconductors using THz laser[7].

Keldysh crossover and dielectric breakdown It is predicted that a crossover from the nonlinear optical response regime, which is itself very interesting showing giant nonlinearitly in Mott insulators[13], to the breakdown regime can take place when the field is strong enough [21]. The quantum mechanical breakdown mechanism known as the Landau-Zener breakdown (or Schwinger mechanism in nonlinear QED) has a threshold $F_{\rm th} \propto \Delta^2$ [24] (see [22] for a review). For typical Mott insulators, using THz laser, the field strength for the “Keldysh crossover”, which devides the nonlinear optical regime to the breadown regime is several 100 kV/cm, while the Landau-Zener threshold $F_{\rm th}$ is about several MV/cm. This is within experimental feasability with recent strong lasers [6, 34], and indeed, dielectric breakdown in vanadium dioxide was experimentally observed quite recently using THz laser with an aid of metamaterial enhancement [17].

Bloch oscillation Bloch oscillation is the coherent periodic motion of particles in a lattice system, and in interating system, becomes dumped due to the Umklapp process [24]. Discussed in **??**.

Wannier-Stark ladder In strong electric fields, the electron wave function becomes localized in the direction of the field, i.e., Wannier-Stark localization. The effect of interaction was studied in [11] and [2].

Band flipping Band flipping in ac-fields takes place due to the renormalization of the hopping parameter with a Bessel function (see Eq. **??**).

Coherent phonon effects Selective excitation of the coherent motion of phonons is becoming an interesting technique and it has been demonstrated that one can change the interaction strength U in organic crystals [12].

Floquet topological phase transition In periodically driven system, the single body band structure is described by the Floquet state (**??**) and one can change the topology of an electron system by chosing the the proper driving field. This was first demonstrated in a two dimensional Dirac system in circularly polarized light where a photo-induced quantum Hall state can be dynamically realized [23]. In the case of a honeycomb lattice, it was further demonstrated that the effective Floquet model is equivalent to the Haldane model [5] of quantum Hall effect without Landau levels [15]. Classification theory for periodically driven toplogical states was undertaken [14], while other example of realization was proposed [16]. In the case of a Dirac electrons in circularly polarized light, the dynamical gap which opens at the Dirac point scales as [23]

$$\Delta_{\rm Dirac} = v_F^2 a^2 e^2 E_{\rm ac}^2/\Omega^3, \tag{1}$$

where v_F is the Fermi velocity. In order to open a gap whose size is 0.1eV in, for example in graphene ($v_F = \sqrt{3}/2\times 2.7eV = 2.3eV,\ a = 2.6\mathring{A}$), the necessary field strength is $E_{\rm FT} \sim 5\times\Omega^{3/2}$MV/cm where the unit of Ω is eV.

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