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The Possibility of CDW Superconductivity

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Abstract: *We investigate pinned charge density waves (CDWs) those are observed in low dimensional materials. We treat pinned CDWs as moving CDWs that were confined within a typical quantum well out of the many different types where pinning occurs at the barrier. We calculate the current flowing out of the quantum well by confined CDWs. Pinned components of CDWs are fewer than 3 dimensions so that unpinned component of CDWs for 3D CDWs can drive CDW superconductivity. For even alkali metals, CDW superconductivity can be possible along the peculiar direction of unpinned component for 3D CDWs.*

Keywords: *Quantum well, CDW superconductivity, Fröhlich, Charge Density Wave, Conductivity.*

1. Introduction

The first seminal theory to explain low transition temperature superconductors was suggested by Fröhlich [1] in 1954 using the concept of sliding charge density waves (CDWs) and then Bardeen, Cooper, and Schrieffer (BCS) [2] elucidated these superconductors very well based on the Fröhlich Hamiltonian. At those times Peierls claimed that metal-insulator transition will occur if there are electron-phonon interactions in one dimension [3]. In modern texts [4] it is introduced that the ion lattice is dimerized by the Peierls instability to drive superlattices. In 1970's conducting polymers were discovered by Heeger et al. [5]. During tracing these polymers, Moceau et al. [6,7] observed anomalous conductivities guessed as closely related to CDWs. Sliding CDWs are pinned by the impurity (impurity pinning) or lattice ions (commensurate pinning). The use of mean field theory or quantum field theory [5] in investigating pinned CDWs is mainstream. However, there is, as yet, no readily acceptable theory of CDW transport in low-dimensional materials. Because thermal fluctuations or quantum fluctuations tend to destroy the existence of long range orders in one-dimensional structures, the observation of one–dimensional CDWs causes a theoretical problem [8]. Peierls-Fröhlich type CDWs are very rare in normal metals, but Overhauser-type CDWs without structural transitions [9] are possible in even alkali metals.

In this paper the conductivity of pinned CDW is calculated under the conjecture that CDWs are confined within a quantum well in the presence of pinning. We also investigate the possibility of CDW superconductivity along the peculiar direction of unpinned component for 3D CDWs.

2. The Possibility of CDW Superconductivity

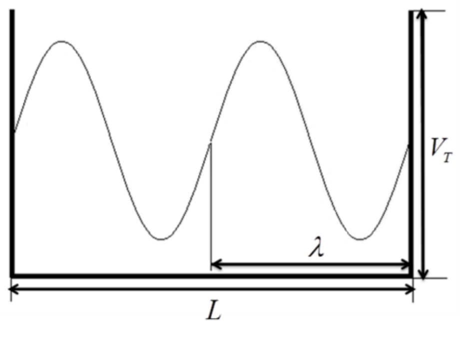

Fig1. *The charge density wave is confined within a standard potential well. We assumed a standard well out of the many different types that occur in the presence of pinned CDWs.*

Of the many different potential wells in a material with CDW, we choose the most typical one, postulating an average and standard potenitial well, to accommodate a commensurate pinning of a CDW as illustrated in Fig.1.

We can then calculate the current density in the presence of applied voltage V to be

$$J = n_h ev - n_e ev + J' = J_0 \tanh\left(\frac{e(V - V_T)}{2k_B T}\right) + J', \quad (1)$$

where n_0 is the total number density of electrons and holes, n_e is the electron number density, n_h is the hole number density, and the average velocity of an electron is assumed to be same as that of a hole,

$n_e = n_0 \frac{1}{1+\exp(\frac{e(V-V_T)}{k_B T})}$, $n_h = n_0 \frac{1}{1+\exp(\frac{-e(V-V_T)}{k_B T})}$, k_B is the Boltzmann constant, V is the applied voltage, T is the temperature, V_T is the height of the potential well, J_0 is a normalization constant, J' is the current from other mechanism, and $J(V=0)=0$. Here the critical voltages are given by

$$\begin{aligned} eV_T &\equiv \mu - \varepsilon \cong \varepsilon_F - \varepsilon \\ eV_{T_{COM}} &\cong \varepsilon_F - (\varepsilon_F - \Delta_{CDW}(T)) \approx \Delta_{CDW}(0) = 3.5 k_B T_{CDW} / 2 \\ eV_{T_{im}} &\cong \varepsilon_F - (\varepsilon_F - \varepsilon_d) = \varepsilon_d = \frac{13.6 eV}{(\varepsilon')^2} \frac{m_e}{m_e^*}, \end{aligned} \quad (2)$$

for commensurate pinning and impurity pinning respectively where μ is the chemical potential, ε is the kinetic energy of an electron, ε_F is the Fermi energy, Δ_{CDW} is the gap driven by CDW, T_{CDW} is the Fröhlich-Peierls transition temperature, ε_d is the donor energy [4], ε' is the dielectric constant, and m_e (m_e^*) is the bare (effective) mass of an electron.

The transport in normal states is explained by a form of quantum well that originates from the pinning of CDW, as shown in Fig.1.

The current density is rewritten by

$$\begin{aligned} J &= J_0\{\tanh[\frac{eV - eV_T}{2k_B T}] + \tanh[\frac{eV_T}{2k_B T}]\} = n_0 e v_F \{\tanh[\frac{eV - eV_T}{2k_B T}] + \tanh[\frac{eV_T}{2k_B T}]\} \\ &= \sigma E \\ &= \sigma \frac{V}{L}, \end{aligned} \quad (3)$$

where v_F is the Fermi velocity, σ is the conductivity, E is the electric field, L is the size of the system, and the effective voltage is changed into $(eV + \frac{1}{\beta_E} k_B T)/e$, as shown in Fig.1.

The average number density of an electron in the absence of H is given by

$$\begin{aligned} \int_0^\infty f(\varepsilon) d\varepsilon &= \int_0^\infty \frac{d\varepsilon}{1+\exp\frac{\varepsilon - \varepsilon_F}{k_B T}} = \int_0^\infty \frac{d\varepsilon}{1+\exp\frac{\varepsilon \pm \mu_B H \pm eEL \pm \hbar\omega - \varepsilon_F}{k_B T_{eff}}} \\ &\equiv k_B T \ln[1+\exp\frac{\varepsilon_F}{k_B T}] = k_B T_{eff} \ln[1+\exp\frac{-(\pm\mu_B H \pm eEL \pm \hbar\omega - \varepsilon_F)}{k_B T_{eff}}], \end{aligned} \quad (4)$$

where $f(\varepsilon)$ is the Fermi-Dirac distribution, $N(\varepsilon)$ the density of states, β_i are positive constant parameters, and ε_F is the Fermi energy.

Here the effective temperature is given by

$$k_B T_{eff} \equiv k_B T \pm \beta_H \mu_B H \pm \beta_E eEL \pm \beta_\omega \hbar\omega. \tag{5}$$

The resistivity is given by

$$\rho = \frac{1}{\sigma} = \frac{1}{\frac{\partial}{\partial V}(LJ)} = \frac{2k_B T}{n_0 e^2 v_F L} \frac{1}{1-\tanh^2[\frac{eV + \frac{1}{\beta_E}k_B T - eV_T}{2k_B T}]}. \tag{6}$$

Let us consider the threshold electric field E_T.

Because of linear to non-linear dependence of voltages, the threshold field is given by

$$\frac{\partial^2 \sigma}{\partial V^2}|_{E=E_T} = 0. \tag{7}$$

The electric field is rewritten as

$$\sinh^2[\frac{eV + \frac{1}{\beta_E}k_B T - eV_T}{2k_B T}]|_{V=E_T L} = \frac{1}{2}$$

$$E_T = E_0 - \{-\frac{1}{\beta_E} + (1-0.316)\}\frac{k_B T}{eL} \tag{8}$$

$$V_T = E_0 L.$$

The relation between impurities and the effective sample size [9] is given by

$$\frac{1}{L^{eff}} = \frac{1}{L} + \frac{1}{L_i} \approx \frac{1}{L_i}$$

$$\frac{1}{L_i} \propto n_i \quad \text{for 2-dimensional pinning} \tag{9}$$

$$\frac{1}{L_i} \propto n_i^2 \quad \text{for 1-dimensional pinning}$$

for two-dimensional pinning potential well,

where L_i is related to impurities and n_i is the concentration of impurities so that

$$E_T = E_0 - \{-\frac{1}{\beta_E} + (1-0.316)\}\frac{k_B T}{eL}\frac{n_i}{n_i(x=0)} \quad or$$

$$E_T = E_0 - \{-\frac{1}{\beta_E} + (1-0.316)\}\frac{k_B T}{eL}\frac{n_i^2}{n_i^2(x=0)}, \tag{10}$$

where x is the doping rate. Since pinning up to 2-dimensions is possible, one peculiar directional CDW without pinning stemmed from 3D CDW can drive CDW superconductivity originally suggested by Fröhlich [1].

3. Conclusion

In conclusions, the pinned CDWs are explained by moving CDWs confined in a quantum well amongst many different types whose potential barrier is induced by impurity pinning or commensurate pinning. Pinned components of CDWs are fewer than 3 dimensions so that unpinned component of CDWs for 3D CDWs can drive CDW superconductivity. For even alkali metals, CDW superconductivity can be possible along the peculiar direction of unpinned component for 3D CDWs. Under the postulation of occurrence of 3D CDWs in alkali metals, seeking the unpinned direction of 3D CDWs had better be recommended and confirmed.

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