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MANY-BODY EFFECTS IN THE SPACE CHARGE LAYERS

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Various investigations related to electron-electron interactions in quasi-two-dimensional systems made on semiconductor surfaces are reviewed mainly from a theoretical point of view.

I. Introduction

In inversion and accumulation layers on semiconductor surfaces a strong electric field quantizes the motion of electrons in the direction normal to the surface. We have a quasi-two-dimensional system in which the electron concentration can be controlled continuously over a wide range. In case of space-charge layers made on Si surfaces the electron concentration N_s varies typically from 10^{10} to 10^{13} cm^{-2}. This system provides a unique system for the study of electron-electron interactions which can strongly depend on the electron concentration. The purpose of this paper is to give a brief review of various investigations related to many-body effects in this system.

Section II discusses recent development in understanding the subband structure and optical transitions, emphasizing roles of exchange and correlation effects. Section III gives some of the topics related to the two-dimensional electron gas or liquid and its instabilities. The two-dimensional system exhibits its most peculiar properties when a magnetic field is applied normal to the system. The orbital motion of electrons is completely quantized into discrete Landau levels. Many-body effects can play a crucial role in such a system with singular density of states. This problem will be discussed in Sec. IV. Some unsolved problems have been known to exist concerning stress effects and the valley degeneracy in n-channel inversion layers on Si. An interesting development took place recently concerning these problems, which will be discussed in Sec. V.

II. Subband Structure and Optical Transitions

After the suggestion on the possibility of quantization of electron motion perpendicular to the surface by Schrieffer [1], Stern and Howard [2] developed a self-consistent scheme of the calculation of the subband structure in the Hartree approximation. This method has been applied to a number of systems. As is well-known, however, the Hartree approximation overestimates Coulomb repulsive force of other electrons and can sometimes be insufficient because of the neglect of exchange and correlation effects. Such many-body effects tend to reduce effects of mutual electron-electron interactions. The many-body effects are crucial in inversion layers on Si because the usual three-dimensional r_s parameter, defined as the average distance between electrons divided by an effective Bohr radius, is larger than unity. One way to include them is to use the method of diagramatic perturbation [3,4]. Although this method is expected to be applicable in inversion layers where subband energy separations are relatively large, it does not work in accumulation layers where energy separations calculated in the Hartree approximation are extremely small. The density-functional formulation has turned out to be the most powerful and successful method [5]. Figure 1 shows an example of the subband structure in an n-channel inversion layer on the Si (100) calculated in the density-functional formulation. One sees that the exchange and correlation are extremely important.

The best way to get information on the subband structure experimentally is to observe intersubband optical transitions. However, the resonance energy is shifted from corresponding subband energy separations due to the depolarization effect. The depolarization effect arises because internal electric fields which an electron feels become different from external one due to resonance polarization of the system. Corresponding to the fact that the exchange and the correlation are important in determining the subband structure, however, a local field correction to the depolarization effect (exciton-like effect) can be important and tends to reduce it [6]. Within an approximation scheme based on the density-functional formulation this local field effect has been evaluated and the resonance energy has been calculated [7]. Figure 2 shows an example of the results in an n-channel inversion layer on the Si (100) surface. The resonance energy is rather close to the subband energy separation at relatively low electron concentrations and becomes larger with increasing electron concentration.

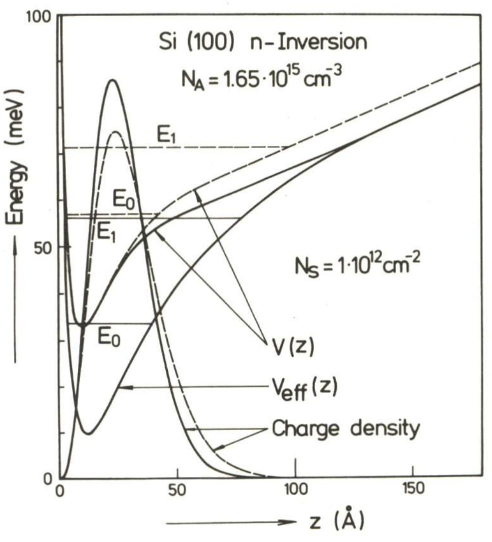

Fig.1 An example of calculated subband structure in the n-channel inversion layer on the Si (100) surface: The solid lines represent the result in the density-functional formulation and the broken lines corresponding Hartree results. After [5]

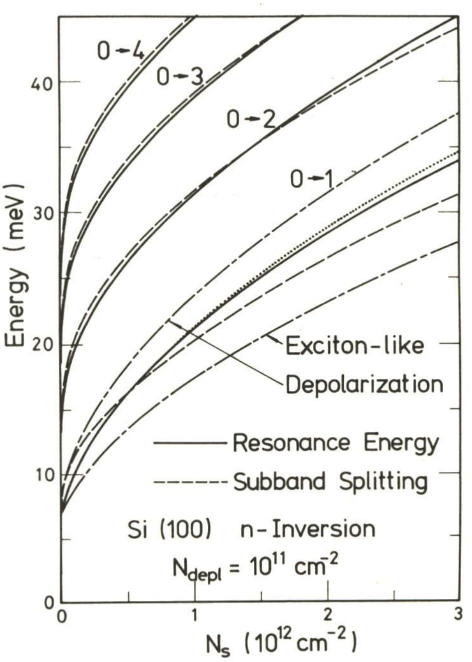

Fig.2 Calculated resonance energies and subband splittings in the n-channel inversion layer on the Si (100): After [7]

Resonance energies were calculated also by Vinter but in insufficient apporoximation [8]. Effects of electron-electron scatterings on the optical transition were recently investigated in a crude approximation and shown to have little effect on the resonance energy except at extremely low electron concentrations but contribute to resonance broadening [9].

Three different methods were used for observing intersubband optical transitions: the direct absorption [10], the photo-conductivity [11], and the emission [12]. At first these three seemed to give different answers to the resonance energy. Recently the discrepancy was shown to arise because the effective field at the interface was different from its thermal equilibrium value in the latter two experiments [13,14]. The density-functional calculation gives results in excellent agreement with experiments for the transition to the first excited subband. For transitions to higher excited subbands the agreement is not so complete.

Because of the additional corrections appearing in the optical transitions a direct comparison has not been possible concerning the subband structure. Therefore, it is desirable to get an independent information on the subband energy separation itself. There have been attempts to determine electron concentrations at which higher subbands become occupied by electrons [15,16]. However, the results of different groups are inconsistent with each other and no definite conclusion has been deduced from such kinds of experiments.

Effects of magnetic fields on the optical transition are one of the best ways to further study the subband structure. In a magnetic field parallel to the surface the subband structure is modified although the field can be treated as a relatively small perturbation. The optical spectrum is both shifted and broadened.

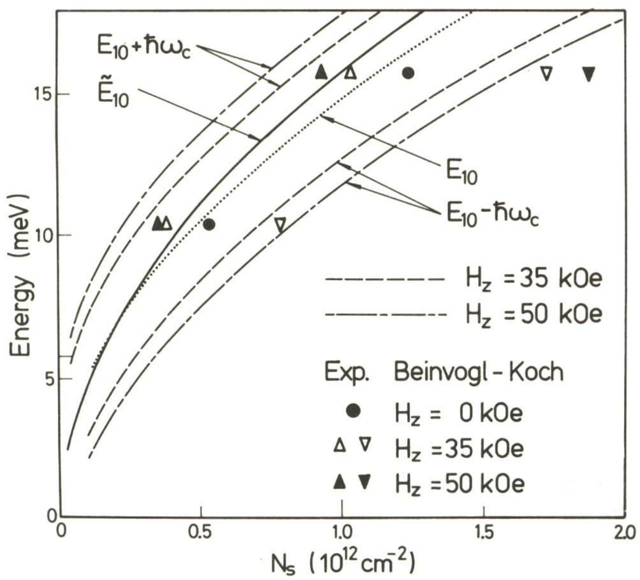

Fig.3 Comparison of the theoretical and experimental positions of the main and combined transitions in the n-channel accumulation layer on the Si (100): After [20]

Such experiments were carried out and strong modification of the spectrum was observed especially in accumulation layers [17]. Corresponding theoretical calculation has given shifts of the resonance positions in reasonable agreement with the experiments [18].

A more detailed study can be made in magnetic fields tilted from the surface normal. In tilted fields combined intersubband-cyclotron transitions which are transitions between different Landau levels associated with ground and excited subbands become allowed. It has theoretically been predicted that the position of the combined resonances is not affected by the depolarization effect and its local field correction when their strengths are sufficiently small [19,20]. Therefore their observation makes it possible to determine the subband energy separation and resonance energy independently. Such experiments were quite recently performed in an accumulation layer [21]. Figure 3 gives comparison of theoretical and experimental positions of the main and combined resonances in two different magnetic fields. Although the theoretical energies are about 10% larger than the experiments, the agreement is satisfactory concerning the relative positions of the main and combined transitions. This means that the theoretical calculation gives subband energy separations and resonance energies which are both in reasonable agreement with experiments.

Temperature effects were also studied theoretically [22-24] in connection with recent observation of intersubband optical absorptions at elebated temperatures [25,26]. The many-body effect has been shown to be still appreciable even at room temperature although it is less important than at low temperatures. Further electron-electron collisions give rise to a large imaginary part of the subband energy. However, no direct comparison between experiments and theory has been made because the depolarization effect and its local field correction have not been evaluated at high temperatures.

III. Two-Dimensional Electron Liquid

Historically, effects of electron-electron interactions on quasi-particle properties such as the effective mass and the g factor first attracted much attention. Smith and Stiles [27] determined the effective mass from temperature dependence of the amplitude of the Shubnikov-de Haas oscillation in n-channel inversion layers on the Si (100) surface. They have demonstrated that the effective mass is considerably enhanced from the bulk value and decreases with the electron density. The mass enhancement has been calculated in different approximations [4,5,28-30]. The calculations give a concentration-dependence of the mass in qualitative agreement with experiments but different absolute values depending on approximations. Recent elaborate experiments of Fang et al. [31] have casted doubt on accuracy of the mass determined from the temperature dependence of oscillation amplitudes. They have suggested that the mass depends on detailed nature of scatterers in the system. At present, therefore, it is not possible to make a detailed comparison between the theory and experiments, although there is no doubt about the roles of electron-electron interactions in the mass enhancement.

There have been investigations on the correlation energy, the pair correlation function, etc. of the two-dimensional electron gas [32-34]. Instabilities of the usual state with paramagnetic and uniform occupations of different spins and valleys have also been studied. Those include spin-, valley-, and charge-densiy wave ground state [35-37] and ferromagnetic phases [38]. However, there has been no experimental evidence for the presence of such phase transitions in actual inversion layers. It is well-known that the usual ground state is unstable against the formation of the Wigner crystal at sufficiently low electron concentrations. This problem has been studied by various people [39-43] especially in connection with anomalous behavior of the conductivity in inversion layers at low concentrations. It is rather difficult, however, to distinguish it from the Anderson localization caused by potential flucuations. Quite recently Bloss et al. [44] suggested that a domain structure associated with phases in which only a single valley is occupied by electrons was responsible to anomalous transport. However, the predicted critical concentration is much larger than estimated by other author [38]. Possible mechanisms of the superconductivty and critical temperatures were also investigated in two-dimension [45,46].

IV. Electron-Electron Interactions in Magnetic Fields

Discrete density of states causes well-known nonsinusoidal oscillations of the two-dimensional conductivity. Its peak exhibits splitting into four or two depending on whether the valley and spin splittings are resolved or not. The splitting diminishes and disappears with increasing electron concentrations. The theory of the quantum transport [47] predicts that the level broadening of Landau level is much larger than the spin Zeemann splitting and the valley splitting. The experimentally observed splittings have been explained by an extremely large enhancement due to exchange effect among electrons in discrete Landau levels [48]. The singular density of states causes a large difference in the occupation ratio of different spins and valleys, which in turn gives rise to a large oscillatory enhancement of the splittings. The exchange effect explains the famous experiments in tilted magnetic fields by Fang and Stiles [49] and the lineshape of the nonsinusoidal Shubnikov-de Haas oscillation if one takes into account the bare valley splitting arising from the existence of large interface barrier potential [50]. The oscillatory enhancment of the g factor has been confirmed experimentally [51].

There have been investigations on many-body effects on the cyclotron resonance. Kohn's theorem [52] says that the electron-electron internal force does not affect the position and the broadening of the cyclotron resonance in uniform systems. In actual inversion layers this theorem is not strictly applicable because of the existence of scatterers. It has been shown theoretically that the discrete density of states gives rise to a subharmonic structure at the low magnetic field side of the cyclotron resonance lineshape [53]. The subharmonic structure has been observed experimentally [54]. A calculation for a model system has shown that the position of the subharmonic structure is determined by the quasi-particle effective mass whereas the main position is essentially given by the bare mass [55]. This explains the experimental fact that the mass obtained from the subharmonic structure is in good agreement with the mass determined by Smith and Stiles. There have been controversies on many-body effects on the main peak of the cyclotron resonance. Kennedy et al. [56] claimed that the cyclotron mass depended on the frequency, whereas Abstreiter et al. [57] observed no appreciable frequency dependence. There have been theoretical attempts to study this difficult problem [58-60] but no definite conclusion has been obtained.

It has been known that the conductivity vanishes in several finite regions of N_S, indicating the existence of localized electrons at the edges of Landau levels [61]. Kawaji and Wakabayashi made a first systematic study of this problem and showed that electrons at tails of Landau levels are localized when the average distance between electrons is larger than the radius of the cyclotron orbit [62]. As a possible explanation they suggested a two-dimensional Wigner crystal pinned by random potential fluctuations. The possibility of the two-dimensional Wigner crystallization in magnetic fields have theoretically been studied by a number of people [63-69]. The Anderson localization has also been proposed as a candidate of the electron localization, and some experimental results [70] are actually favorable to the localization due to potential fluctuations. Quite recent observation of an anomalous cyclotron resonance at extremely low electron concentration [71] may not be explained by such Anderson localization and may be a first evidence of the existence of strongly correlated ground state such as the Wigner crystal.

V. Problem of the Valley Degeneracy and Stress Effects

The many-valley structure of the Si conduction band gives different valley degeneracy factors (g_V) depending on surfaces. The effective-mass theory predicts g_V=2 on the (100), g_V=4 on the (110), and g_V=6 on the (111). On the (100) surface g_V=2 has been confirmed experimentally. Until quite recently, however, all the experiments failed to observed any valley degeneracy factor other than 2 on the both (110) and (111). Similar problems arise on the (100) surface under externally applied uniaxial stresses where one can expect simultaneous occupations of different sets of vallyes and electron transfer among them [72]. In contrast to the theoretical expectation the degeneracy factor remained 2 under stresses. To explain these peculiar behaviors Kelly and Failcov [73,74] suggested a charge-density wave ground state in which different valleys are coupled via phonon-mediated extremely large intervalley exchange interactions. Although the assumed values of the intervalley coupling constant are extremely large and are not readily acceptable, this model has explained almost all the experimental results that are unexlained in ordinary theory.

Recently there appeared various experiments which contradicted previous experiments and the Kelly-Falicov theory. Tsui and Kaminsky [75] observed g_V=6 on the Si (111). They suggested that inhomogeneous strains localized in the vicinity of the interface were responsible to previously observed removal of the valley degeneracy on the (110) and (111) surfaces. Stallhofer et al. [76] observed two peaks in the cyclotron resonance under stress on the Si (100) in contrast to previous experiments [77] which gave a single peak. This suggests the simultaneous occupation of different sets of valleys under stress in contradiction to the Kelly-Falicov theory. The experimental results can be explained rather by ordinary electron-electron interactions [78-80]. However, there are still various unexplained facts and the problem of the valley degeneracy and the stress effect remains completely open at present.

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