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On the gate capacitance in *n*-channel inversion layers on ternary semiconductors under magnetic quantization

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An attempt is made to derive a generalized expression of the magnetogate capacitance in the *n*-channel inversion layers on ternary semiconductors without any approximations of weak or strong electric-field limits and taking into account the influences of electron spin and Dingle temperature, respectively. It is found on the basis of the three-band Kane model and taking *n*-channel inversion layers on $Hg_{1-x}Cd_xTe$ as an example, that the gate capacitance exhibits oscillations with the changing magnetic field and the oscillatory behavior is in qualitative agreement with the experimental observation reported in the literature for metal-oxide-semiconductor structures of the same semiconductor.

I. INTRODUCTION

In recent years, there has been considerable interest in studying the various physical features of inversion layers on Kane-type semiconductors under magnetic quantization.[1,2] Although extensive work has already been done, the interest for further research of the different aspects of such layers is becoming increasingly important. One such important parameter is the magnetogate capacitance of metal-oxide-semiconductor (MOS) structures on small-gap semiconductors which has been investigated[3,4] on the basis of the two-band Kane model together with various assumptions and also by neglecting the combined influence of the electron spin and broadening effects. It would, therefore, be of great interest to investigate the gate capacitance in *n*-channel inversion layers on ternary semiconductors in the presence of a uniform dc quantizing magnetic field along the *z*-direction using the three-band Kane model which has been stated in the literature to be the most valid model of ternary semiconductors.[5] Since the above class of materials are being increasingly used for the fabrication of semiconductor devices technical applications and also since the band gap in these materials can be made as narrow as desired by varying the alloy composition, the influence of band nonparabolicity becomes significant. In what follows, we shall first derive an expression of the surface electron concentration per unit area in the *n*-channel inversion layers on ternary semiconductors under magnetic quantization without any approximations of weak or strong electric-field limits as often used in the literature[4] and by taking into account the influence of electron spin and Dingle temperature, respectively. We shall then derive a model expression of the magnetogate capacitance with the proper use of the electron statistics and then study theoretically the effect of a quantizing magnetic field on the same capacitance, taking *n*-channel inversion layers on $Hg_{1-x}Cd_xTe$ as an example.

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II. THEORETICAL BACKGROUND

The density-of-states function of the 2D electrons in the inversion layers on semiconductors can, in general, be expressed[2] as

$$D(\epsilon)=\frac{eHg_v}{2\pi\hbar}\left(\frac{2}{\pi}\right)^{1/2}\times\sum_{n=0}^{n_{\max}}\sum_{i=0}^{i_{\max}}\frac{1}{\Gamma_n}\exp\left(-\frac{2}{\Gamma_n^2}(\epsilon-\epsilon_{n,\pm})^2\right),\quad(1)$$

where g_v is the valley degeneracy, e is the electron charge, H is the quantizing magnetic field along z-direction, Γ_n ($\equiv K_BT_D$, Ref. 6) is the linewidth of the broadened Landau levels, K_B is the Boltzman constant, T_D is the Dingle temperature, n is the Landau quantum number, and $\epsilon_{n,\pm}$ is the unperturbed energy eigenvalue, which in the present case can be determined from the equation[7]

$$B(\epsilon_{n,\pm})-(n+1/2)\hbar\Omega-\sigma g^*(\epsilon_{n,\pm})H\mu_0=0,\quad(2)$$

in which notations are the same as in Ref. 7. Thus, combining Eqs. (1) and (2) with the Fermi–Dirac occupation probability factor, the surface electron concentration per unit area under magnetic quantization can be written as

$$N_S=C_0\sum_{n=0}^{n_{\max}}\sum_{i=0}^{i_{\max}}\rho_\tau\Gamma_n^{-1},\quad(3)$$

where

$$C_o\equiv(g_veH/2\pi\hbar)(2/\pi)^{1/2}(K_BT),$$

T is the temperature,

$$\rho_\tau\equiv\left[\left(\sum_{\tau=0}^{\infty}\phi_+(\tau)+\sum_{\tau=1}^{\infty}\phi_-(\tau)\right)-\left(\frac{\sqrt{\pi}}{2a}\right)[1-\operatorname{erf}(b)]\right],$$

$$\phi_\pm(\tau)\equiv\{(2\pi)^{1/2}L_\tau(2a)^{-1}\exp(\delta_{,\pm}^2)[1\mp\operatorname{erf}(\delta_{,\pm})]\},$$

$$L_\tau\equiv(-1)^\tau\exp(-b^2),$$

$$b\equiv\gamma^{-1}(\eta-\theta_n),$$

$$\gamma\equiv\Gamma_n(K_BT\sqrt{2})^{-1},\quad\theta_n\equiv\epsilon_{n,\pm}(K_BT)^{-1},$$

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$\delta_{,\pm} \equiv (Z_{,\pm}/2a), \quad Z_{,\pm} = 2ab \pm \tau, \quad a \equiv \gamma^{-1},$

$\eta \equiv E'_F (K_B T)^{-1}, \quad E'_F \equiv [eV_g - N_S e^2 (d_{\text{ins}}/\epsilon_{\text{ins}}) - E_{fB}].$

V_g is the gate voltage, d_{ins} and ϵ_{ins} are the thickness and permittivity of the insulating layer, respectively, and E_{fB} is the energy separation between the Fermi level and the conduction band edge in the bulk of the p-type substrate material in the presence of a quantizing magnetic field. It may be noted in this context that the gate capacitance (C_g) in MOS structures can, in general, be expressed[2] as

$$C_g^{-1} = C_{\text{ins}}^{-1} + C_s^{-1}, \tag{4}$$

where $C_{\text{ins}} \equiv (\epsilon_{\text{ins}}/d_{\text{ins}})$ is the fixed capacitance due to the insulating layer, C_s ($\equiv edN_s/dV_0$) is the surface capacitance due to space-charge layer, and $V_0 \equiv [V_g - (eN_s d_{\text{ins}}/\epsilon_{\text{ins}})]$ is the surface potential. Thus combining Eqs. (3) and (4), the magnetogate capacitance in the n-channel inversion layers on ternary semiconductors in the presence of a quantizing dc magnetic field can be written as

$$C_g(H) = \left(A_0 \sum_{n=0}^{n_{\max}} \sum_{i=0}^{i_{\max}} \zeta_\tau \Gamma_n^{-1}\right) \times \left(1 + \frac{A_0 e d_{\text{ins}}}{\epsilon_{\text{ins}}} \sum_{n=0}^{n_{\max}} \sum_{i=0}^{i_{\max}} \zeta_\tau \Gamma_n^{-1}\right)^{-1}, \tag{5}$$

where

$$A_0 \equiv eC_0/K_B T,$$

$$\zeta_\tau \equiv \left(\exp(-b^2) + \sum_{\tau=0}^{\infty} X_+(\tau) + \sum_{\tau=1}^{\infty} X_-(\tau)\right),$$

and

$$X_\pm(\tau) \equiv \{L_\tau a^{-2} \sqrt{\pi}\, \delta_\pm [1 \mp \text{erf}(\delta_{,\pm})] \mp L_\tau a^{-2} - bL_\tau \exp(\delta_{,\pm}^2)[1 \mp \text{erf}(\delta_{,\pm})]\}.$$

Finally, it may be noted that the general forms of the electron statistics and gate capacitance in the n-channel inversion layers on parabolic semiconductors under magnetic quanti-

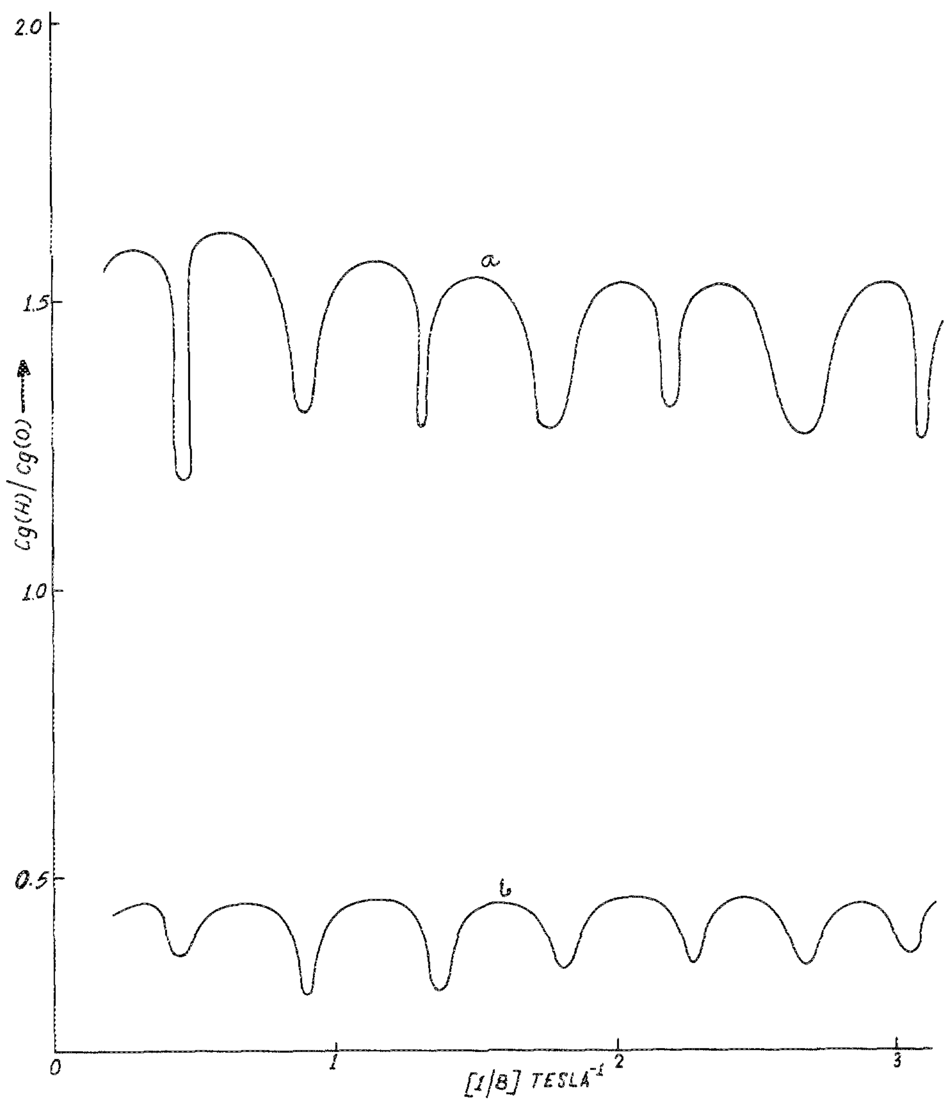

FIG. 1. The plot (a) exhibits the dependence of the normalized magnetogate capacitance of n-channel inversion layers in $Hg_{1-x}Cd_xTe$ on the reciprocal quantizing magnetic field. The plot (b) corresponds to parabolic energy bands.

zation, including both spin and broadening effects, will be given by Eqs. (3) and (5), where

$$\epsilon_{n,\pm} = (n+\tfrac{1}{2})\hbar\Omega - \sigma\mu_0 g_0 H, \quad (6)$$

where g_0 is the magnitude of the spectroscopic splitting factor at the band edge.

III. RESULTS AND DISCUSSION

Using Eqs. (3) and (5) together with the parameters[8–11]:

$$Eg(x) = [-0.304 + 0.0005\ T + x(1.914 - 0.001\ T)]\text{eV},$$

$$m_o^*(x) = [3\hbar^2 Eg(x)/4P^2(x)],$$

$$P(x) = [(\hbar^2/2m)(18+3x)]^{1/2},$$

$$\Delta = 0.9\ eV,$$

$$\epsilon_{sc} = (20.262 - 14.812\,x + 5.2795\,x^2)\epsilon_0,$$

$$T_D = 3\ K,\ d_{ins} = 15\ \mu\text{m, and } T = 4.2\text{ K},$$

as appropriate for $Hg_{1-x}Cd_xTe$ together with $F_s = 5.6\times10^5$ V/m and $\epsilon_{ins} = 2.8\,\epsilon_0$ (the permittivity of Mylar, for example, which is commonly used as the equivalent oxide layer in MOS structures of small-gap semiconductors), we have plotted the normalized gate capacitance for $x = 0.26$ as a function of reciprocal magnetic field as shown in Fig. 1, in which the same plot for inversion layers on parabolic semiconductors has further been considered for the purpose of comparison. It appears from Fig. 1 that the band nonparabolicity enhances the numerical values of the normalized magnetogate capacitance in n-channel inversion layers on ternary semiconductors and the oscillatory dependence of the gate capacitance is observed to be somewhat similar to the experimental observation in $Hg_{1-x}Cd_xTe$ MOS structures having n-channel inversion layers.[1] With a varying magnetic field, each Landau level crosses the Fermi level, and a change is reflected in the capacitance through the redistribution of the carriers among the Landau levels.

The theoretical investigation presented would be of great significance as the interest on gate capacitance has been growing in recent years from the point of view of technical applications and of exploration of other fundamental aspects of semiconductor surfaces in MOS structures. Our numerical computations are valid for $x > 0.17$, but the theoretical results can be used for inversion layers on Kane-type semiconductors. It may be stated in this context that, although a more rigorous treatment of the electron-electron interactions, formation of band tails, dependence of Γ_n on various physical parameters, and hot-electron effects should be considered along with a self-consistent procedure, this simplified analysis exhibits the major features of the magnetogate capacitance with reasonable accuracy. The basic purpose of the present work is not solely to demonstrate the effect of magnetic quantization on the gate capacitance, but also to formulate the carrier statistics in its most generalized form without any approximations of weak or strong field limits by including both the spin and broadening effects, in n-channel inversion layers on ternary semiconductors using the three-band Kane model since the various transport phenomena and the derivation of the expressions of many important physical parameters are based on the electron statistics in such materials.

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