THE EFFECT ON INCOMPRESSIBLE STRIPS OF THE DISTANCE BETWEEN THE METALLIC GATES AND THE TWO-DIMENSIONAL ELECTRON SYSTEM

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Abstract

In this study, the effect of the distance of metallic gates to the two-dimensional electron system on incompressible strips in the quantum Hall regime was investigated. In the calculations, the two-dimensional spatial distributions of the electron density and potential profile were determined by solving the three-dimensional Poisson equation for all charges defined in the three-dimensional heterostructure with a self-consistent method. In the presence of a perpendicular magnetic field, two different regimes occur on the electron distribution. These are incompressible strips and compressible regions. The thickness of the incompressible strip and the velocity of the electron in this region vary for various magnetic field values. It has been demonstrated that the thickness of the incompressible strips and the velocity of the electron in these regions change when the distance of the metallic gates defined on the three-dimensional heterostructure to the two-dimensional electron system changes. The results of the calculations carried out are consistent with the previous studies.

Keywords: quantum Hall effect, metallic gate, incompressible strip

INTRODUCTION

Experiments with a scanning force microscope [1,2] in narrow Hall samples and subsequent theoretical studies [3,4] made significant contributions to the understanding of Incompressible Strips [5,6] formed at low temperature and high magnetic field values. It is possible to create a two-dimensional electron system (2DES) with materials with different energy band gaps in three-dimensional (3D) heterostructure [7-13] Hall Bar geometry can be defined by the potential difference or chemical etching method to be applied to the metallic gates placed on this structure [14-16]. The spatial distribution of electrons created by these two methods is locally different. Concurrent, the electron distribution generated by the chemical etching method will show a different distribution according to the amount of etching to be made from the surface to the 2DES. Likewise, this applies to metallic gates. The spatial distribution of electrons will vary as the distance of the metallic gates to 2DES changes.

Chklovskii et al. [5] have shown that when a steep magnetic field is applied to an electron distribution confined by the edges, two different regimes form on the density profile. These are incompressible strip (IS) and compressible regions (CS). Including the screening property, electrons are placed locally up to the Fermi energy level. ISs occur in regions where Fermi energy coincides between two Landau energy levels, which are formed by the effect of the magnetic field. CSs occur in other regions. Therefore, there is no accessible state in ISs, the electron distribution in these regions does not change according to the position. Concurrent, since screening is weak in these regions, the potential profile changes according to position. On the other hand, since accessible states already exist in CSs, the electron distribution in these regions changes with position. In contrast to IS, CS has a higher degree of screening, so the potential profile does not change depending on the position. They demonstrated that one of the most crucial factors determining how thick the ISs would be is the change in electron distribution at the margins according to location.

With Landau quantization [17], the electron density in two dimensions in the presence of a perpendicular magnetic field is defined by the filling factor (ν). When Zeeman splitting, that is, spin effects are not taken into account, the positions corresponding to ν=2,4,6,.. locally are the regions of ISs.

In this study, 2DES was created in a 3D heterostructure defined by $GaAs/Ga_{1-x}Al_xAs$ semiconductor materials. Hall Bar geometry was defined in 2DES with the negative voltage applied to the metallic gates placed on the 3D structure. In the presence of a perpendicular magnetic field, the thickness of the ISs and the electron velocity in these regions were calculated as a function of both the magnetic field and the distance of the metallic gates to the 2DES.

THEORY AND MODEL

The main purpose of this study is to determine the effect of the distance (ΔZ_G) between metallic gates and 2DES on ISs. For this, the thickness of the ISs and the electron velocities in these regions were calculated for perpendicular and different magnetic field magnitudes and ΔZ_G values. First, with an initial condition in which donors and boundary conditions in the 3D heterostructure were defined, the 3D Poisson equation was solved in the absence of magnetic field and at zero temperature by a self-consistent method [18]. The magnification parameters of the 3D heterostructure used for this study are given in Fig.1. The spatial distribution of the electron density and the potential profile were determined from the solution of the Poisson equation. At zero temperature, the electron charge density locally positioned up to the Fermi energy is $n_{el}(r)$,

$$\nabla^2 V(r) = -\frac{\rho(r)}{\varepsilon} \qquad (1)$$

it is obtained by the Poisson equation. Here, $\rho(r) = -e[n_{el}(r) - n_0]$ is the screening charge density, n_0 is the donor charge density, ε is the dielectric constant, $V(r)$ is the potential energy for electrons, and e is the electron charge. Using Landau quantization [17], when a magnetic field is applied perpendicular to the spatial distribution of the resulting electron density,

$$\nu(x,y) = 2\pi l_B^2 n_{el}(x,y) \qquad (2)$$

the local fill factor with 2D is determined [6]. Here $l_B = \sqrt{\hbar/eB}$ is the magnetic length, $2\pi\hbar$ Planck's constant and the magnitude of the magnetic field in the B (z) direction. Chklovskii et al. [5], with Thomas Fermi approximation (TFA) [19], defined the thickness of ISs with the expression

$$w_\nu^2 = \frac{2\varepsilon\hbar\omega_c}{\pi^2 e^2 \frac{dn_{el}(x)}{dx}\Big|_{x=x_\nu}} \qquad (3)$$

when the filling factor is an integer. Here, ε(= 12.4 for $GaAs$) is the dielectric constant of the material, $\omega_c (= eB/m^*)$ is the cyclotron frequency, m^* (= $0.067m_0$ for $GaAs$) is the effective mass of the electron, m_0 is the free electron mass. x_ν is the position of the electron density when the filling factor is an integer With this equation, only the thickness of the ν=2 ISs and the electron velocity in these regions are calculated according to both the magnetic field and the distance of the metallic gate to the 2DES. The drift velocity of the electron in ISs is determined by [20]

$$\vec{V}_D = \frac{\vec{E} x \vec{B}}{B^2} \qquad (4)$$

In Fig.1, the magnification parameters of the 3D heterostructure with 128x128x100 mesh, the positions of the metallic gates, the positions-amounts of the donors and the position of the 2DES are given. Here ΔZ_G is the distance between the metallic gates and 2DES. The distance between the two metallic gates placed on the structure is approximately $1.06\mu m$. In the calculations, the value of the aluminum concentration in the 3D heterostructure was taken as x=0.3 in accordance with the experiments. The donors identified in the structure are in a single grid in the (x-y) plane, known as delta doping in the literature [7,8].

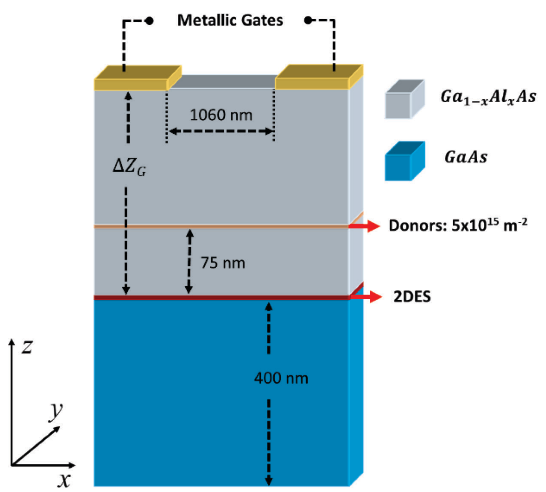

Fig. 1. *Schematic representation of the amplification parameters of the 3D heterostructure.*

The metallic gate voltage is taken as $V_g = -1.0\, Volt$ for all calculations. In the light of these definitions, the spatial distribution of the electron density obtained from the solution of the Poisson equation for $\Delta Z_G = 165nm$ is shown in Fig.2a and the potential profile in Fig.2b. For the magnetic field applied homogeneously and perpendicular to the obtained electron density, a local 2D filling factor is determined by Landau quantization. The variation of the filling factor for B=1.5 Tesla taken from the $y = 0.75\mu m$ position in Fig.2a according to the one-dimensional position at different ΔZ_G values is shown in Fig.3. As the metallic gates move away from the 2DES, the electron distribution moves towards the edges and the amount of density in the center increases. This situation changes the variation of the electron distribution according to the position in the positions where the filling factor is ν=2. The thicknesses of the ISs calculated as a function of the magnetic field for the ΔZ_Gvalues in Fig.3 are shown in Fig.4a and the velocities of the electrons in these regions are shown in Fig.4b.

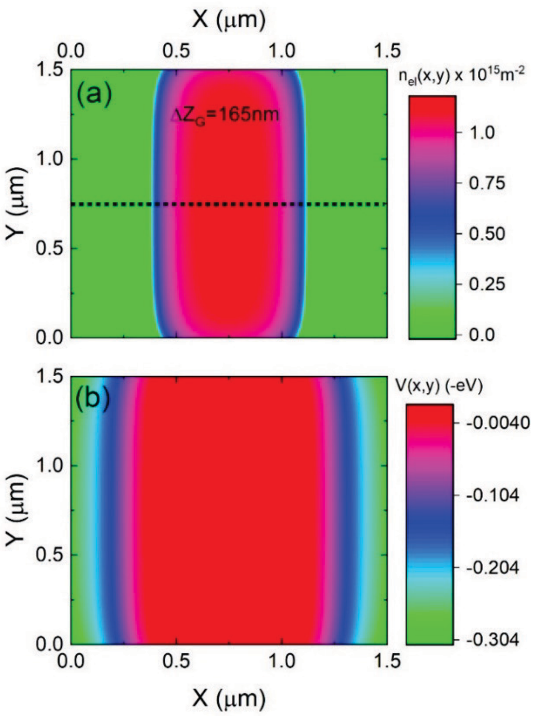

Fig. 2. *For values of* $\Delta Z_G = 165nm$ *and* $V_g = -1.0\, Volt$ *(a) spatial distribution of electron density, (b) potential profile.*

As the magnetic field increases, the thickness of the ISs increases, and the speed of the electron in these regions decreases. As the metallic gates move away from 2DES, ν=2 protects its existence at larger magnetic field values.

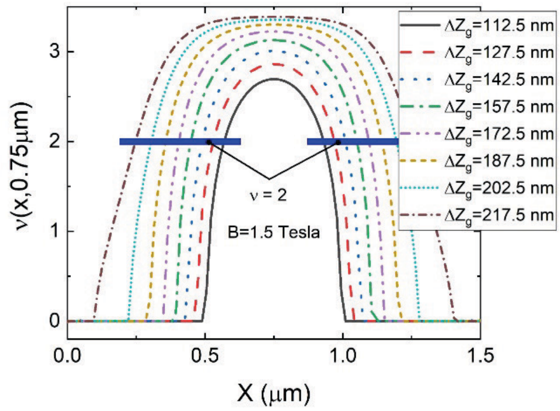

Fig. 3. *Variation of filling factor with position for different* ΔZ_G *distances at* $V_g = -1.0\, Volt$*, B=1.5 Tesla.*

The thickness of the IS formed at different magnetic field values for ν=2 at the $y = 0.75\mu m$ position is shown in Fig.5a as a function of the distance between the metallic gates and the 2DES. Likewise, the velocity of the electron in ISs is shown in Fig.5b. In Fig.5a, the thickness of the ISs decreases up to approximately $\Delta Z_G = 180nm$ and increases again after this value. In response to this situation, the electron velocity in ISs shows the opposite feature. In Fig.5a, both the edge effects of the 3D heterostructure and the negative voltage applied to the metallic gates are effective together as the main reason for the decrease in thickness in ISs between $\Delta Z_G = 112{,}5nm$ and $\Delta Z_G = 180nm$. After the value of $\Delta Z_G = 180nm$, the thickness of the ISs increases as the contribution from the metallic gates decreases due to the increase in the distance between the metallic gate and the 2DES. In this case, it is reflected in the velocity of the electron in ISs, as seen in Fig.5b.

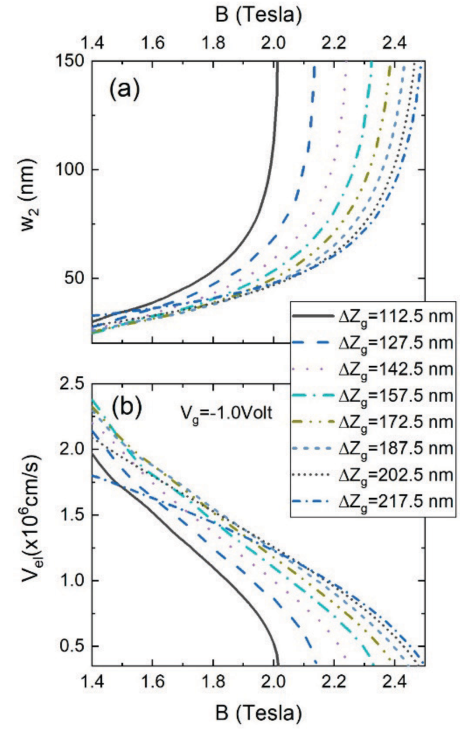

Fig. 4. *Variations of (a) thickness of ISs, (b) drift velocity of electrons in ISs according to magnetic field for different* ΔZ_G *values at* $V_g = -1.0\ Volt$.

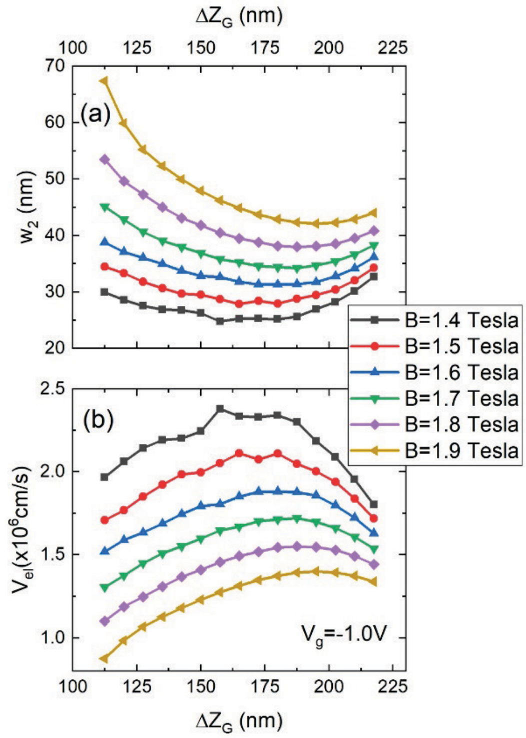

Fig. 5. *Variations of (a) thickness of ISs, (b) drift velocity of electron in ISs according to* ΔZ_G*distance for different magnetic field value at* $V_g = -1.0\ Volt$.

RESULTS AND CONCLUSION

When a magnetic field perpendicular to the Hall Bar geometry formed by the metallic gates defined on 2DES is applied, the thickness of the ISs was calculated according to both the magnitude of the magnetic field and the distance of the metallic gates to the 2DES. According to the calculation results, the thickness of ISs increases with the magnitude of the magnetic field and the velocity of electrons in these regions decreases with the magnitude of the magnetic field. At constant magnetic field value, the thickness of ISs decreases when metallic gates are close to 2DES up to a certain distance. After this distance, the thickness of the ISs increases. In response to this situation, the electron velocity in ISs shows the opposite feature. By changing the distance between the 2DES and the metal gate for a constant magnetic field value, it is possible to change the IS thickness and electron velocity in these regions. By varying the distance between the 2DES and the metal gate, the IS thickness and electron velocities in these regions were calculated for the first time in this work.

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