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THEORETICAL INVESTIGATION OF METALLIC CONTACTS UNDER INHOMOGENEOUS CONDITIONS

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Abstract
In this study, the properties of ideal and non-ideal contacts are investigated under nonlinear regime and inhomogeneous conditions. In the absence of an external magnetic field for gate and etching defined devices, the three-dimensional Poisson equation solves self-consistently for the given material parameters and the potential profile of the structure is obtained. In the presence of a vertical magnetic field, the spatial distribution of incompressible strips is determined taking into account the electron-electron interaction within the Thomas-Fermi screening theory. Using a local version of the Ohm's law, the current distribution is calculated with a corresponding conductivity model. It is observed that the incompressible strips can be on the edge or at the center of bulk considering different magnetic fields.

Keywords: Quantum Hall Effect, Screening, Metallic Contact

INTRODUCTION

Current and probe contacts are essential ingredients of many experimental setups concerning charge transport at low dimensional systems. The recent experimental investigations [1-5] show that, the charge distribution in the close vicinity of the contacts present inhomogeneties due to annealing processes. Such a result, clarifies that contacts cannot be taken as ideal. However, the state of art contacts are still perfectly Ohmic with a finite, nevertheless small, contact resistance.

FORMULATION OF THE PROBLEM

The main purpose of this letter is to obtain the spatial distribution of the potential, density and current within the Hall bar geometry in the presence of metal contacts. However, to obtain such quantities, one has to solve Poisson and Schroedinger equations self-consistently first, and then obtain the current distribution via solving the local Ohm's law. The most challenging part of this scheme is to obtain the current distribution considering the non-linear response regime, which essentially requires that the potential distribution is affected by the imposed high current. Hence, the potential and density profile profiles should be re-calculated while a current is driven.

We first start with an electrostatic equilibrium distribution, where fixed charges (the donors) and the boundary conditions are given. Assuming charge neutrality, the Fermi energy is fixed by the number of donors and in the absence of external magnetic field and at vanishing temperature one can obtain the electron density from the Poisson equation utilizing the given boundary conditions imposing that the potential is periodic. Fig. 1 presents the numerically obtained confinement potential Here we superimposed an impurity potential which simulates the inhomogeneous distribution of donors, stemming from the experimental findings.

The electrons are filled up to Fermi Energy at zero temperature via Eqn. 1, and hence the initial density distribution is obtained via;

$$^2V(r) = -\frac{\rho(r)}{\varepsilon_0}. \qquad (1)$$

Using this density profile and equipped with the Landau quantization, one gathers the information on the local filling factors which essentially connects the magnetic field to the local densities by;

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

with the magnetic length $l_B = \sqrt{\hbar/eB}$. Once the local filling factors are known, using the well justified local Ohm's law one can obtain the local current distribution by;

$$^{\rightharpoonup}\mu^{*}(r)/e = \vec{j}(r) = \hat{\sigma}(r).\vec{E}(r), \quad (3)$$

where $\mu^{*}(r)$ is the position-dependent electrochemical potential, $\hat{\sigma}(r)$ is a two by two tensor describing the local conductivities, and $\vec{j}(r)$ is the local current density together with the local electric field $\vec{E}(r)$.

In the presence of an external magnetic field in z-direction and a current in y-direction results in a potential generated in x-direction, namely the Hall potential. If the Hall potential generated is much smaller than the screened potential ($V_H << V_{Scr}$) one can readily obtain the self-consistent current distribution. However, once the imposed current (i.e. the potential difference between source and drain) becomes comparable with the screened potential on has to solve the above equations self-consistently.

In our work, we map a Hall bar on a 128x128 grid and solve the potential-density and density current equations self-consistently using a 3D fast Fourier transformation numerical method. The details of our scheme can be found elsewhere [5].

RESULTS AND DISCUSSION

A Hall bar geometry was designed to create 2DES 150 nm below the surface, where surface potential is pinned to the mid-gap of GaAs (-0.75 V).

The narrow Hall bar is defined by etching at the sides having a depth similar to 65 nm. The contacts are simulated by metallic regions that reside 48 nm below the surface and are kept at -0.5 V. In previous studies we calculated the current distribution across the Hall bar, where current amplitude is limited to the linear response regime [4]. Here, we extended the study to the non-linear response regime, where the external current modifies the electronic charge distribution considerably.

The non-ideal contacts are described by density fluctuations near the transition region, as indicated by experiments [1-3] which essentially influence the current distribution drastically. In Fig.2 shows the spatial distributions of electron (a) and current densities (b) considering different impurity centers for the same magnetic field value in an inhomogeneous condition. The magnetic field is set to a value where only two incompressible stripes reside along the Hall bar and the dissipative current is transmitted via the hot spots formed at the corners of the system. Such a magnetic field value corresponds to an interval at the lower edge of the quantum Hall plateau, which is essentially observed at the local scanning probe experiments by several groups. This regime is also well described by the Landaurer-Buettiker formalisim, however, in that scheme the current is supposed to be dissipationless.

Fig.3 presents a case where the bulk of the sample becomes incompressible, hence the current is confined to the center of the sample. This magnetic field value corresponds to an interval close to the end of the quantum Hall plateau (high magnetic field end). This regime is also well described by the localization theory of the quantum Hall effect. Note that, in our calculations we did not use and arguments of the localization theory. The only role of the impurities is to modify the confinement potential together with defining the local conductivities.

As a result of our calculations we can clearly state that the impurities stemming from the inhomogeneous distribution of the donors yield potential fluctuations, which are small compare to the homogeneous donor distribution. Hence the main mechanism defining current distribution comes from the non-linear effect of the developed Hall potential, whereas the properties of the local conductivities are still impurity dependent.

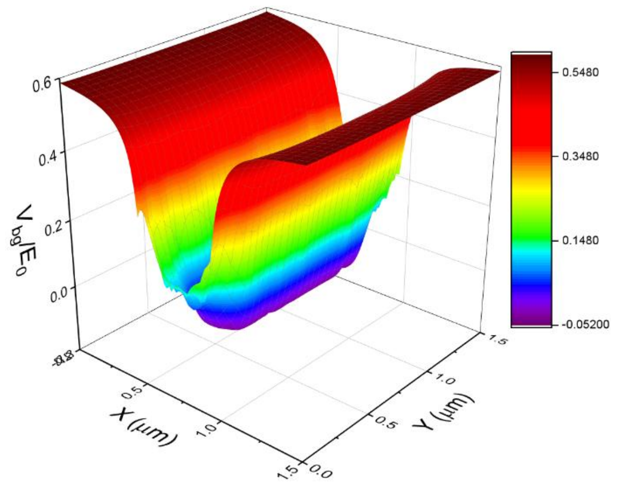

Fig. 1. *Spatial distribution of the confinement potential considering 300 impuritty centers distributed randomly at the Hall bar.*

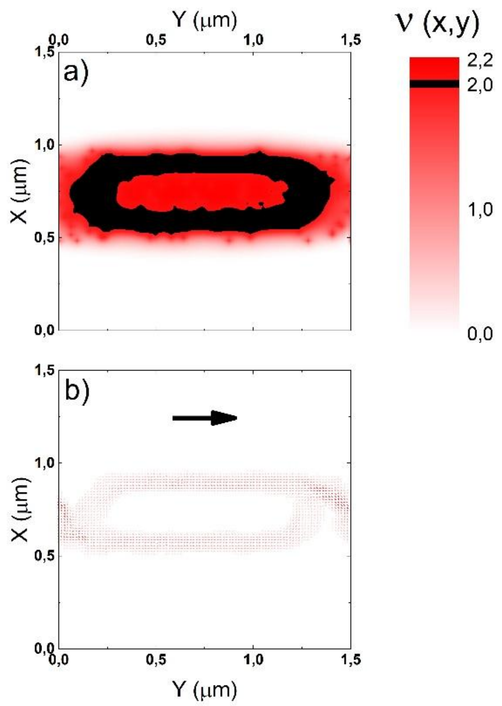

Fig. 2. *Spatial distributions of the local filling factors ν(x,y) (a), together with the current density (c) as a function of lateral coordinates. Color scale denotes density gradient, whereas arrows (red) present the amplitude and direction of the imposed excess current. We distribute (a) 150 and (b) 300 number of impurities in the bulk.*

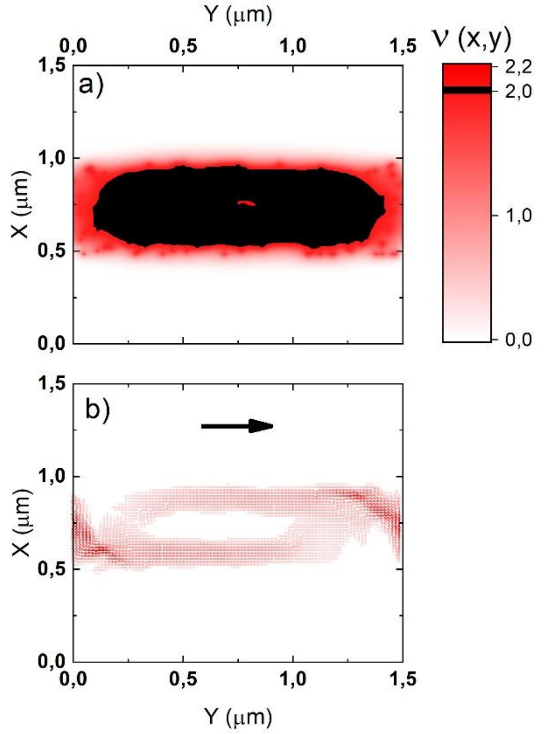

Fig. 3. *Spatial distributions of the local filling factors ν(x,y) (a), together with the current density (b) as a function of lateral coordinates. Color scale denotes density gradient, whereas arrows (red) present the amplitude and direction of the imposed excess current. We distribute (a) 150 and (b) 300 number of impurties in the bulk. The calculations are performed same as Fig 2.*

CONCLUSION

It is seen that the inhomogeneous condition causes the change of electron distribution along the Hall bar. This affects the spatial distribution of the current density. In addition, a phenomenological model is presented to discuss the inhomogeneous condition. It is believed that efforts will contribute to the understanding of ideal and non-ideal contacts, especially in the quantum hall regime.

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