Effect of strain on a two-plate capacitor with two-dimensional electron gas (2DEG)

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Abstract

The aim of the present paper is devoted to study the capacitance for Two-dimensional electron gas (2DEG)**,** 2DEG with electron area density n separated from perfect metal electrodes by an insulator of thickness d is described. The capacitance of two plate capacitor is described and studied as a function of strain. The standard capacitance can be enhanced or lowered by altering the conducting materials of the electrodes and varying the geometry of the capacitor. The capacitance of a 2DEG capacitor is studied as a function of electron area density of the capacitor. The calculated capacitance diverges for low electron area density and converges for higher one.

Keywords: capacitance, strain, 2DEG

{**Citation:** Atef F. Amin. Effect of strain on a two-plate capacitor with two-dimensional electron gas (2DEG). American Journal of Research Communication, 2014, 2(1): 59-66} www.usa-journals.com, ISSN: 2325-4076.

Introduction

The capacitance is the ability of a body to store an electrical charge. A common form of energy storage device is a parallel-plate capacitor. Capacitance can be calculated if the geometry of the conductors and the dielectric properties of the insulator between the conductors are known. In this paper we present the general equation for the capacitance of the capacitor that considers the quantum mechanical energies of the electronic systems involved. This equation applies to two-plate capacitors as,

$$C_g = \frac{\varepsilon_0 \varepsilon_r A}{d} \quad (1)$$

Here ε_0 is the dielectric constant of the vacuum, ε_r is the dielectric constant of the material between the two electrodes of area $A = 10nm^2$ and $d = 4nm$ is the distance between the two-plate capacitor of capacitance C_g .

In a standard parallel plate capacitor, the capacitance C is equal to the geometrical capacitance Eq.(1). As the sizes of the devices approach the nanometer length scale, quantum mechanical phenomena becomes increasingly relevant. The well-known classical models of semiconducting devices and the corresponding scaling laws break down. Ballistic transport processes, for example, gain importance, as does the statistical distribution of the dopant atoms in the small drain-source channels. Quantum effects also alter the capacitance of large, macroscopic capacitors that reach the quantum regime because their dielectrics become thin [1].

For given ε_r and A the capacitance of capacitor reaching the quantum regime may be differ considerably from the well known value of capacitance Eq. (1).

The capacitance can be changed (enhanced or lowered) by altering the dielectric material of electrodes and by varying the geometry of the capacitor [1].

The expression $C = C_g$ is correct when both electrodes are made from a “perfect” metal, which by definition screens electric field with a vanishing screening radius, so that the charge of a given electrode is located exactly on the electrode surface and the electric field from the opposite electrode does not penetrate into the metal. If one of the electrodes is made from a material with finite positive Debye screening radius R_D for example, a doped bulk semiconductor, then the imperfect charge screening at this electrode allows the electric field to penetrate a distance R_D into the electrode and the capacitance doesn't equal the geometrical capacitance any more. If one describes the capacitance by the effective capacitor thickness:

$$d^* = \frac{\varepsilon A}{4\pi C} \quad (2)$$

where $\varepsilon = \varepsilon_0 \varepsilon_r$, then the effect of positive screening radius is to increase the effective capacitor thickness from $d^* = d$ to $d^* = d + R_D$ [2], where R_D is the Debye screening radius. An exact evaluation of quantum capacitance is however of fundamental importance for nanoelectronic devices such as nanowires.

Theoretical treatment

For two-plate capacitor, if one of the electrodes consists of a clean, low density, 2DEG, the capacitance can be written as [3-9]:

$$\frac{1}{C} = \frac{1}{C_g} + \frac{1}{C_q} \tag{3}$$

where C_g is the geometrical capacitance and C_q is the quantum capacitance.

$$C_q = Ae^2 \frac{dn}{d\mu} \tag{4}$$

where μ is the electrochemical potential of the 2DEG, $n = 3x10^{-3} nm^{-2}$ is the electron area density. In these systems the capacitance is enhanced. However, the size of enhancement is usually a few percent larger than that of geometrical capacitance [3, 4, 6, 9].

To calculate the capacitance for such a model, we first describe the total electrostatic energy $U(N)$ associated with the ground state configuration of n electrons per unit area. Using the equilibrium condition $d(u - QV)/dQ = 0$ along with $dQ = eAdn$ gives

$$V = \frac{dU}{dQ} = \frac{1}{eA}\frac{dU}{dn} \tag{5}$$

Then the differential capacitance can be written as

$$C = e^2 A^2 \left(\frac{d^2 U}{dn^2} \right)^{-1} \tag{6}$$

The effective capacitor thickness d^* can also be defined by the total energy as [2]

$$d^* = \frac{\varepsilon}{4\pi e^2 A}\frac{d^2U}{dn^2} \tag{7}$$

In the ground state for low-electron area density, the repulsion between electrons within the 2DEG separates the electrons from their nearest neighbors by distance $n^{-1/2}$ as shown in Fig.1.

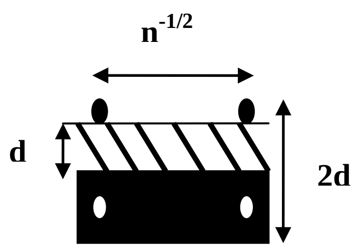

Fig.1 Two neighboring electrons (black circles) in a 2DEG formed at the semiconductor-insulator interface. The electrons are separated from a metal electrode (solid area) by an insulator of thickness d (hatched area). The electrons formed positive image charge in metal (white circle).

This separation distance will be increase to $n^{-1/2}(1+\zeta)$ after applying a strain to the system, where ζ is the strain. Each electron with charge e induces an image charge +e on the metal surface. Within the 2DEG, a given electron and its image charge form an electron-image charge dipole and the total electrostatic energy can be obtained by first calculating the electrostatic potential ϕ experienced by each electron relative to infinity.

$$\phi = \frac{e}{2\varepsilon d} - \frac{e\left(n^{-1/2}(1+\zeta)\right)^{-1}}{\varepsilon} g(x) \tag{8}$$

where $g(x)$ is dimensionless function

$$g(x) = 4\sum_{i=1}^{\infty}\sum_{j=0}^{\infty}\left(\frac{1}{\sqrt{i^2+j^2}} - \frac{1}{\sqrt{i^2+j^2+4x^2}}\right) \tag{9}$$

Where $x = \left(n^{-1/2}(1+\zeta)\right)^{-1}$

The total energy of the configuration of electron is

$$U = -\frac{1}{2}eA\left(n^{-1/2}(1+\zeta)\right)^{-2}\phi \tag{10}$$

Combining Eq. (10) and Eq. (7) gives

$$\frac{d^*}{d} = \frac{1}{32\pi}[\frac{3g(x)}{x} + 5g'(x) + xg''(x)] \tag{11}$$

Then the differential capacitance Eq. (6) can be calculated.

Results and discussion

The differential capacitance C as a function of electron area density n is computed as shown in Fig.2, the capacitance diverges for low electron density and converges for high electron density following the same manner as capacitance-voltage characteristics [10].

Fig.2 shows a growth in capacitance at low electron concentration per unit area, this dramatic capacitance growth is due to the coupling of each electron in the 2DEG to its image charge in the metal electrode, at low electron density, compact electron-image dipoles are separated from each other by a distance much larger than their dipole arm. These dipoles interact weakly with each other, providing only a small resistance to capacitor charging. [2].

The capacitance-strain relation is shown in Fig.3, the capacitance increases with strain, this property can be used in strain sensors, and in application circuit based on integrated bipolar arrays incorporating the new capacitive strain sensors which can be designed and tested [11].

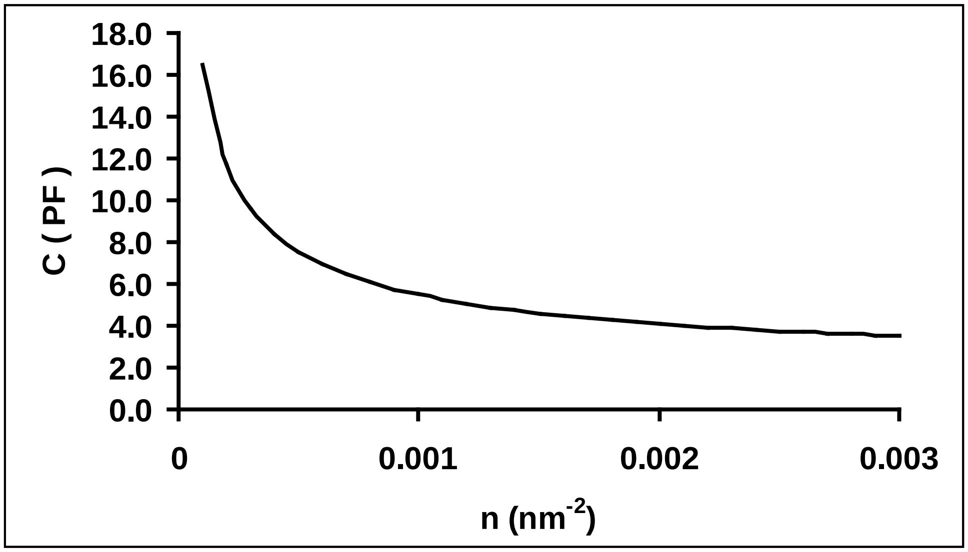

Fig.2 Capacitance as a function of electron area density.

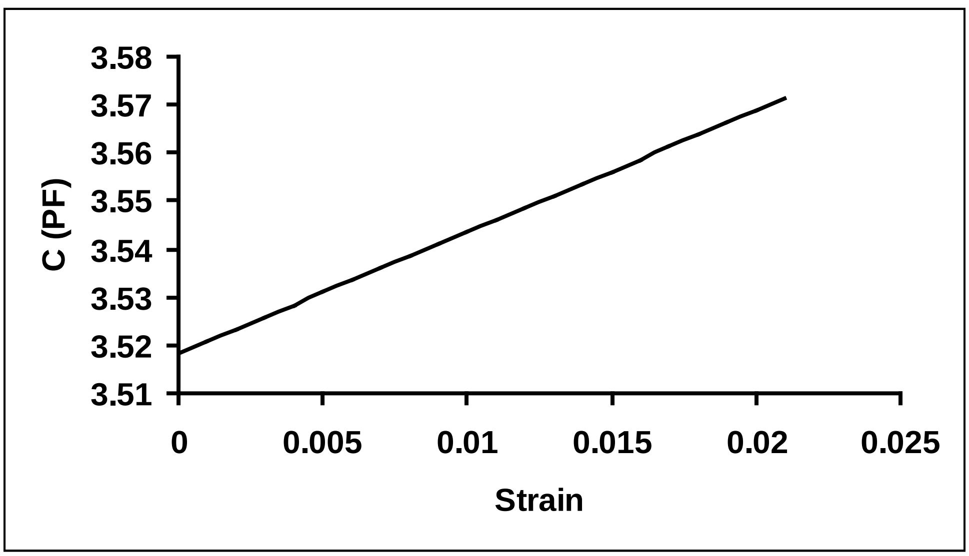

Fig.3 Capacitance as a function of strain.

Acknowledgements

I would like to express my great thanks to Prof. Dr Adel Phillips Professor of Physics - Engineering Physics and Math. Dept., Faculty of Engineering, Ain Shams University for his help and his useful discussion of this work.

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