Research Journal of Applied Sciences, Engineering and Technology 5(2): 481-484, 2013
DOI:10.19026/rjaset.5.4977
ISSN: 2040-7459; E-ISSN: 2040-7467

Submitted: May 08, 2012 Accepted: June 08, 2012 Published: January 11, 2013

Research Article

Study of Static Dielectric Constant of n-Type InAs

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Abstract: The aim of this study is studying the influence of the donor concentration and temperature on the static dielectric constant (ε_s) of heavily doped n-type InAs semiconductor. The variation of donor concentration caused an exponential increase of ε_s at high values of donor density. Our calculations indicated that ε_s has no meaning at concentration above 3×10^{16} cm^3. Above this value the static dielectric constant diverges so that the polarization catastrophe occurred. The static dielectric constant dependence of resistivity shows that at high resistivity the static dielectric constant appears to be nearly constant and equals the value $\varepsilon_s = 14.5$. This value is equal to the static dielectric constant of InAs host semiconductor without doping. One can expect a divergence of ε_s at very low resistivity values at which polarization catastrophe can happen.

Keywords: Heavily doped InAs, polarization catastrophe, static dielectric constant

INTRODUCTION

The dielectric properties of the various materials used in semiconductor fabrication and packaging play an important role in achieving the desired performance of integrated circuits. A basic understanding of dielectric properties is therefore needed by most engineers and scientists working in the field of semiconductor science and technology. One important property of a dielectric material is its dielectric constant (ε) which is a measure of the ability of a material to be polarized by an electric field. If a material is subjected to d.c., electric field, the dielectric constant is known as static dielectric constant. The dielectric constant becomes a function of frequency in the materials when a.c., field is used because polarization is affected by frequency (Frohlick, 1956).

Low-ε dielectric means low permittivity, or low ability to be polarized and hold charge. Low-ε dielectrics are very good insulators for isolating signal-carrying conductors from each other. Thus, low-ε dielectrics are a necessity in very dense multi-layered IC's, wherein coupling between very close metal lines need to be suppressed to prevent degradation in device performance. On the other hand, a high-ε dielectric means high permittivity. Because high-ε dielectrics are good at holding charge, they are the preferred dielectric for capacitors. High-ε dielectrics are also used in memory cells that store digital data in the form of charge (Prince and Due-Gundersen, 1983).

One of the major effects of heavy doping in semiconductors is that the dielectric constant changes with impurity density and thus with the average spacing between impurities. The change is significant for impurity densities greater than the critical carrier density given from Mott criterion (Shklovskii and Efros, 1984). The influence of the impurity concentration on the static dielectric constant in semiconductors in heavy doping regime has been treated by several authors at low temperatures (Castellan and Seitz, 1951; Bethin *et al.*, 1974; Castner, 1980; Teng and Li, 1985).

In the low range of temperatures a large number of non-ionized impurity atoms, responsible for the increase in the value of static dielectric constant, are present. Castellan and Seitz (1951) showed a low temperature classical relation describes the change of the static dielectric constant considering the contribution of the impurity atoms to the polarization. Dhar and Marshak (1985) have extended this relation by taking into account the polarization of the host atoms and its effect on the polarization of the impurity atoms (and vice versa). This correction makes an appreciable difference in ε.

In this study the static dielectric constant of heavy doped InAs semiconductor at room temperature is discussed.

THEORETICAL MODEL

The static dielectric constant dependence of impurity concentration has been pointed out by Castellan and Seitz (1951) taking into account the contribution of the impurity atoms to the polarization. Their formula for the static dielectric constant ε_s is on the form:

$$\varepsilon_s(N) = \varepsilon_{const} + \frac{N\alpha}{1-\frac{N\alpha}{3\varepsilon_{const}}} \tag{1}$$

where,

α : The polarizability of the impurity atom

ε_{const} : The dielectric constant of the pure host semiconductor

N : The concentration of non-ionized impurity atoms

Dhar and Marshak (1985) have extended Eq. (1) by considering the polarization of the host atoms and its effect on the polarization of the impurity atoms. They obtained the static dielectric constant as:

$$\varepsilon_s(N) = \varepsilon_{const} + \frac{N\,\alpha\,(\varepsilon_{const}+2)(4\varepsilon_{const}-1)}{9\varepsilon_{const} - N\alpha(\varepsilon_{const}+2)} \tag{2}$$

where, α is given by:

$$\alpha = \frac{4\pi A}{1 - BN^{1/3}} \tag{3}$$

with A and B are constants.

RESULTS AND DISCUSSION

The system under investigation is the n-type InAs. We assume that no compensation is present i.e., $N_A = 0$ where N_A is density of acceptors, so that the excess electrons are assumed to equal:

$$n = N_D - N_A = N_D \tag{4}$$

For doped Indium Arsenide the critical concentration N_c might be first calculated from Mott criterion (Shklovskii and Efros, 1984):

$$a_B^* N_c^{1/3} = 0.25 \tag{5}$$

where, a_B^* is the effective Bohr radius, for InAs we have $a_B^* = 34.96\,nm$, hence the critical concentration is estimated as $N_c \cong 3.657 \times 10^{14}/cm^3$. According to this calculation, to satisfy the condition of heavily doping we have to choose donor concentrations greater than the value $3.657 \times 10^{14}/cm^3$.

For static dielectric constant calculations, we followed reference (Ristic *et al.*, 2004) in which they used Eq. (2) and (3) to calculate the static dielectric constant at room temperatures in the case of heavily doped InAs. Values used in the computation are shown in Table 1.

Assuming that the resistivity ρ (Ω.cm) of the n-doped InAs is predominantly affected by electrons as majority carriers, it can be calculated as Ristic *et al.* (2004):

$$\rho = [q\,N_D\,\mu_n]^{-1} \tag{6}$$

Table 1: Values used in the computations

Quantity	Value
ε_{const}	14.5
A	2×10^{-17} cm^3
B	5×10^{-7} cm

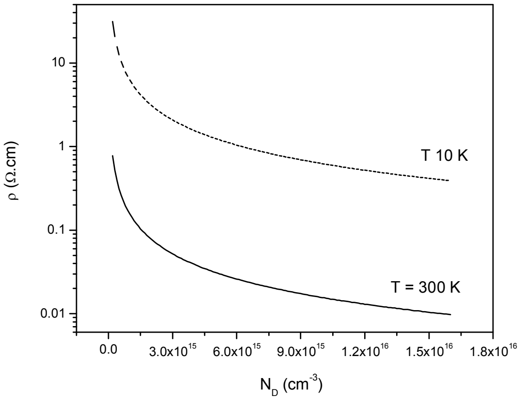

Fig. 1: The donor concentration dependent electrical resistivity at T = 300 K and T = 10 K

where,

q : The electronic charge

μ_n : The mobility of electrons

We considered the scattering centers of carriers in InAs as lattice scattering as well as impurity ions scattering. Set the mobility of electrons as $\mu_n = 4\times10^4$ cm^2/V.s at room temperature and $\mu_n = 10^3$ cm^2/V.s at 10 K we can compute the donor dependent resistivity of n-InAs semiconductor. Figure 1 represents the electrical resistivity of n-InAs as a function of donor concentration at T = 300 K and T = 10 K. From the Fig. 1 can notice the exponential decrease of the resistivity by increasing the donor concentration indicating that the semiconductor tends to be more electrically conductive in the case of heavily doping. The same trend is noticed at both temperatures (300 K and 10 K).

The influence of donor concentration on the static dielectric constant is demonstrated in Fig. 2 at room temperature. As the donor density increases the static dielectric constant increases.

The exponential increase of ε_s at higher values of donor density can give an idea about a possible divergence of ε_s at high values of N_D. Our calculations indicated that ε_s has no meaning at N_D above $3\times10^{16}/c^3$. Above this value the static dielectric constant diverges so that the so called *polarization catastrophe* is occurred.

It is known that in disordered systems the metal-insulator transition could be occurred by varying the impurity concentration (Abboudy, 1996). At a certain value of the donor density the metal-insulator transition can happen. Inspection of Fig. 2 shows that at very low

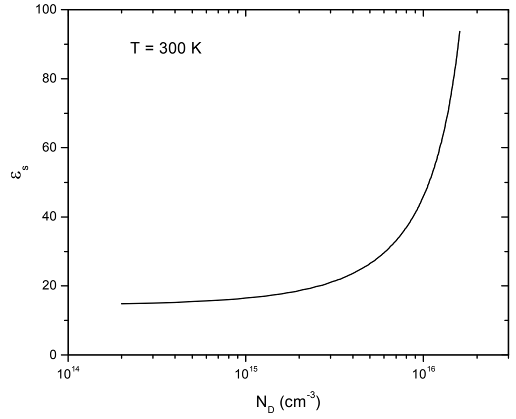

Fig. 2: The static dielectric constant as a function of donor concentration at T = 300 K

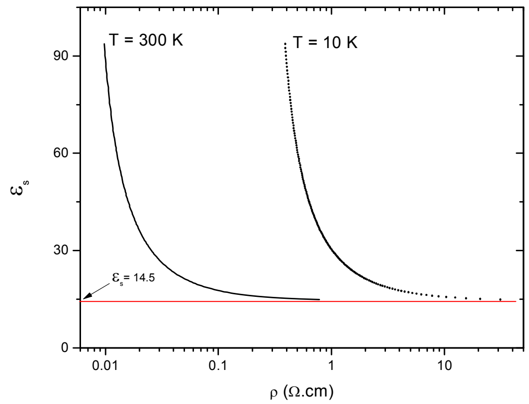

Fig. 3: The static dielectric constant as a function of resistivity at T = 300 K and T = 10 K

values of N_D the material is in the insulator side and the static dielectric constant is nearly constant at the value of the host semiconductor without doping ($\varepsilon_s = 14.5$), as the donor concentration is increased the conductivity is increased and the material dielectric constant is noticeably enlarged to a certain critical value of N_D where the static dielectric constant diverges and hence the material becomes metallic like, this insulator-metal transition can be seen in Fig. 2.

The dependence of the static dielectric constant on impurity concentration can be studied from the variation of ε_s with the electrical resistivity. Figure 3 shows the relation between the static dielectric constant and the resistivity at room temperature and 10 K. At high resistivity the static dielectric constant appears to be nearly constant and equals the value $\varepsilon_s = 14.5$. This value is the same one of InAs host semiconductor without doping. As the resistivity decreases, the static dielectric constant is increasing exponentially. One can expect a divergence of ε_s at very low resistivity values at which polarization catastrophe can happen. This result matches well with that obtained from Fig. 2 at high impurity concentrations.

CONCLUSION

The static dielectric constant of heavily doped n-type Indium Arsenide was calculated as a function of donor concentration and resistivity. The electrical resistivity of n-InAs as a function of donor concentration at T = 300 K and T = 10 K showed an exponential decrease of the resistivity by increasing the donor concentration. As the donor density increases the static dielectric constant increases exponentially. The polarization catastrophe may be occurred at concentrations greater than 3×10^{16} cm^3.

The impurity concentration dependent static dielectric constant was studied from the variation of the static dielectric constant with the electrical resistivity. At high resistivity the static dielectric constant appears to be nearly constant and equals the value $\varepsilon_s = 14.5$ which is the same value of pure InAs sample. As the resistivity decreases, the static dielectric constant is increasing exponentially.

ACKNOWLEDGMENT

The author wishes to acknowledge the financial support of the Research Center of Teachers College, King Saud University.

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