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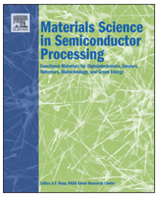

Characterization of p-$Al_xGa_{1-x}As$/p-GaAs structure studied by surface photovoltage in metal–insulator–semiconductor configuration

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ABSTRACT

Metal–insulator–semiconductor (MIS) configuration has been used to measure the surface photovoltage (SPV) spectroscopy of p-GaAs substrate and p-$Al_xGa_{1-x}As$/p-GaAs structure. The p-AlGaAs layer was on p-type GaAs substrate grown by metal organic chemical vapor deposition. An ideality factor was used to investigate the relationship of the measured SPV signals to the "real" SPV signals. Dependence of the surface photovoltage on incident photon intensity for band-to-band excitation was adopted for the calculation of ideality factor. The ideality factor of MIS configuration was found to be 0.008 for our sample with both sides polished in air ambient. In order to calculate the parameters of p-$Al_xGa_{1-x}As$/p-GaAs structure, the minority carrier diffusion length in the GaAs substrate was determined from a linear plot of inverse SPV vs. inverse absorption coefficient by intercepting the line with the x-axis. Other parameters of p-$Al_xGa_{1-x}As$/p-GaAs were studied through the simulation of surface photovoltage.

1. Introduction

Band bending, which is caused by surface charge, has been observed at the surface of the semiconductor. There are downward band bending at the surface of p-type semiconductors. The illumination-induceed change in surface band bending, known as surface photovoltage (SPV) is a nondestructive, contactless technique to determine the characterization of semiconductor [1–7]. There are two common methods for SPV signal measurement [8,9]: Kelvin probe and metal–insulator–semiconductor (MIS) configuration. Kelvin probe is used for the measurement of contact potential difference. But there is a need of Ohmic contact on the back side of the semiconductor sample [11], which is not easy to be achieved, especially on p-III–V semiconductor (p-AlGaAs, for example). When using the MIS configuration to measure the photovoltage of semiconductor caused by chopped light [4], an insulated spacer (sometime simply air or vacuum) was placed between the semiconductor and metal electrode.

At the same time, MIS configuration bring capacitive coupling between semiconductor and metal electrode. The relationship between "real" SPV (V_{real}) signal and measured photovoltage (V_{ms}) signal is affected by the capacitance, the input resistance of voltmeter, and the modulation frequency [1]. It is difficult to determine the capacitance and the relation between V_{real} and V_{ms}. An ideality factor (η) was used to investigate the relationship between the V_{ms} and V_{real}. The ideality factor contains the influence of capacitance, the input resistance of voltmeter, and the modulation frequency. Here V_{ms} was measured as

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a function of incident photon flux density. Then ideality factor was calculated by fitting the curve of V_{ms}. The team of Foussekis and Reshchikov et al. [10–13] used the ideality factor in their Kelvin probe measurement. But the ideality factor is close to unity [10] because Ohmic contact was formed when measured by Kelvin probe. The ideality factor in this study is different because we adopted the MIS configuration rather than Kelvin probe.

SPV signal of p-$Al_xGa_{1-x}As$/p-GaAs structure is produced by surface space charge region (SCR) of AlGaAs layer (via light absorption), the quasi-neutral bulk (via the Dember effect) and the buried p-AlGaAs/p-GaAs interface (via light absorption) [14]. The absorption in p-AlGaAs layer dominates the SPV at higher energy of incident photon, and the p-GaAs layer dominates the SPV at lower energy [15]. In this work, the p-AlGaAs layer is removed from the p-AlGaAs/p-GaAs structure and SPV of p-GaAs substrate are measured, solely the contribution of p-GaAs substrate to the structure is demonstrated. At the same time, the characterization of p-AlGaAs/p-GaAs with the ideality factor in the MIS configuration is researched. The minority carrier diffusion length and drift current, interface recombination velocity etc, are among the discussion.

2. Theory

Assuming the p-AlGaAs layer of p-AlGaAs/p-GaAs structure is thin, can't satisfy the condition of much larger than the photon absorption length. So the excess carriers can present at buried AlGaAs/GaAs interface as well. Therefore, the surface SCR and interface SCR both can contribute to measured SPV signal. Dember photovoltage due to diffusion with different mobilities of electrons and holes depends on the excess carrier density in the bulk of semiconductor. In the case of experiment is taken at low illumination intensity, Dember effect is negligible [16]. The continuity equation for the excess minority carrier density forwarded by Moss is adopted for calculating parameters in SPV measurement [17].

The SPV is calculated in a similar way as the open circuit voltage of an illuminated photodiode [18,19], the surface photovoltage is shown as:

$$V_{ms} = \eta V_{real} = \frac{\eta k_B T}{q} \ln\left(1 + \frac{J_s}{J_0}\right) \tag{1}$$

where V_{ms} is measured photovoltage, V_{real} is “real” photovoltage. η is the ideality factor. In MIS configuration, the capacitance, the input resistance of voltmeter, and the modulation frequency affect the relationship between V_{real} and V_{ms} [1]. K_B, T and q are the Boltzmann constant, temperature and electron charge, respectively. J_s is photogenerated current. J_0 is drift current [20]. Because of the neglect of Dember effects, the measured SPV at the surface is an algebraic sum of the signals accumulated in the surface SCR and interface SCR [1].

2.1. GaAs substrate

In this work, the p-GaAs substrate was obtained by etched the p-AlGaAs layer from the p-AlGaAs/p-GaAs structure. The etched side is front side. The band diagram of p-GaAs substrate under super-bandgap illumination was shown schematically in Fig. 1. The photoelectrons, indicated by thick grey arrows, transited to the conduction band. The sample is illuminated from the front side. Here, the light intensity P means incident photons measured in per square centimeter per second (cm^{-2}/s), not commonly measured in watts per square meter (W/m^2).

Electron–hole pairs generated by absorbed photons within the diffusion length are quickly separated by the built-in electrical field across the surface SCR. Electrons move toward the surface and recombine with surface holes since the surface states are positively charged acceptors in p-type GaAs (for surface defect and adsorbed species etc.), thus reduce the band bending and produce a SPV signal. Here we solve the one-dimensional continuity equation [17] for excess electrons $\delta n(x)$ (photogenerated minority carrier in the p-type GaAs). For the thick GaAs substrate, the surface (front surface) and back surface boundary condition are shown as:

$$D_n \left.\frac{d\delta n(x)}{dx}\right|_{x=0} = S\delta n(0) \tag{2}$$

$$\delta n(x)|_{x=\infty} = 0 \tag{3}$$

Here S assumed constant is surface recombination velocity (via defect level or Auger recombination) [21]. The surface recombination velocity is a true recombination, not the one interpreted as a drift velocity for electrons reaching the SCR edge [1].

The photogenerated carrier diffusion current density J_s from the bulk which is equivalent to short-circuit current density can be simply written as:

$$J_s = qD_n dn(x)/dx|_{x=0} \tag{4}$$

Solve one-dimensional continuity equation with the boundary conditions, current density J_s can be derived from Eq. (4). Substitute J_s into Eq. (1):

$$V_{ms} = \frac{\eta k_B T}{q} \ln\left(1 + \frac{qSL^2P(1-r)}{J_0(LS+D_n)(L+\alpha^{-1})}\right) \tag{5}$$

Because $J_s \lll J_0$, considering the effect of parameter P and r, the measured SPV signals can be normalized as a function of diffusion length L and absorption coefficient α.

After measuring the surface photovoltage spectrum, the L can be determined from a linear plot of V_{norm}^{-1} versus α^{-1} [22–23].

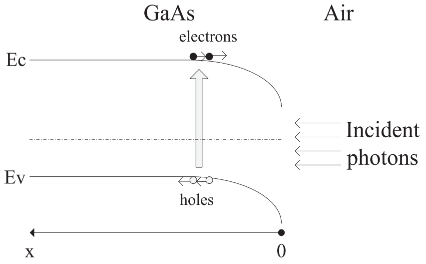

Fig. 1. Schematic band diagram of GaAs substrate under super-bandgap illumination, indicate main transitions by arrow line.