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Electron beam modification of GaAs surface potential: Measurement of Richardson constant

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The surface potential of GaAs is strongly modified in the presence of a high-energy electron beam due to the creation of electron-hole pairs in the depletion region and the subsequent drift of the holes to the surface where they neutralize surface states. This effect is modeled in terms of a parameter $K=A^*T^2/I_b(dE/dz)\eta$, where I_b is the beam current density, A^* is the effective Richardson constant, dE/dz is the beam energy loss per unit length, and η^{-1} is the average energy required to create an electron-hole pair. For the sample studied here, an 0.25-μm layer with $n\simeq 3\times 10^{17}$ cm^{-3}, we obtain a value $K\simeq(7.5\pm 0.8)\times 10^4$ cm at $T=296$ K and $I_b=0.33$ μA/cm^2, which gives $A^*\simeq 0.44$ A/cm^2 K^2. Although this value of A^* is much lower than the theoretical estimate of 8 A/cm^2 K^2, it is in good agreement with other recent results.

INTRODUCTION

Numerous electron-irradiation studies have been carried out in GaAs materials and devices, both for fundamental defect characterizations,[1] and for radiation-hardness determinations.[2] Recently, we have demonstrated an *in situ* Hall-effect system, which allows measurements to be made while the beam is on.[3] In this way, very detailed defect production data have been conveniently and automatically obtained, and the accuracy is higher because the sample does not have to be mounted and demounted several times during the run. However, the beam itself can sometimes modify the apparent electrical properties by increasing the volume carrier concentration (analogous to photoconductivity) and by reducing the surface and interface potential energies. The former effect is negligible for electron or hole concentrations $>10^{12}$ cm^{-3} and typical beam current densities (~ 1 μA/cm^2), but the latter effect can be quite important for thin samples [i.e., approximately for $d\lesssim(10^8/n)^{1/2}\simeq 0.3$ μm, if $n\simeq 10^{17}$ cm^{-3}]. Although it is straightforward to correct for the changes in potential, it is also of use to glean information from their magnitudes. In this paper, we will present a simple model explaining this phenomenon and obtain a value for an important parameter in semiconductor physics, the Richardson constant.

THEORY

The sample to be discussed in this study was a typical molecular-beam-epitaxial (MBE) layer used for GaAs metal-semiconductor field effect transistor (MESFET) fabrication. It consisted of an 0.25-μm-thick active layer, with an electron concentration of about 3×10^{17} cm^{-3}, on a 650-μm-thick, semi-insulating (SI) GaAs substrate. However, as is well known for GaAs, some of the electrons will flow to surface acceptor states and some to interface acceptor states, leaving regions of width w_s and w_i, respectively, depleted of free carriers.[4] Thus, as illustrated in Fig. 1, the *effective* electrical depth is $d_{\rm eff}=d_a-w_s-w_i$, so that the sheet electron concentration, as measured by the Hall effect, is $n_s=nd_{\rm eff}$, or

$$n=n_s/(d_a-w_s-w_i)=n_s\Bigg/\left\{d_a-\left[\frac{2\epsilon(\phi_s-\phi_a-kT/e)}{en}\right]^{1/2}-\left[\frac{2\epsilon(\phi_i-\phi_a-kT/e)}{en}\right]^{1/2}\right\}, \quad (1)$$

where w_s and w_i are derived from the usual depletion-approximation solution of Poisson's equation.[5] Here the parameters ϕ_s, ϕ_i, and ϕ_a are represented as positive quantities for convenience, even though the potentials themselves are inherently negative. The quantity ϵ is the dielectric constant (1.143×10^{-12} F/cm in GaAs), e is the electronic charge (1.602×10^{-19} C), $kT/e=0.025\,51$ V at 296 K, $\phi_s\simeq\phi_i\simeq 0.7$ V, and ϕ_a, to sufficient accuracy, is given by[5]

$$\phi_a=\frac{kT}{e}\left(\ln\frac{N_C}{n}-\frac{n}{N_C\sqrt{8}}\right), \quad (2)$$

where $N_C\simeq 4.16\times 10^{17}$ cm^{-3} at 296 K. For $n=3\times 10^{17}$ cm^{-3}, $\phi_a\simeq 0.0018$ V and $w_s\simeq w_i\simeq 0.0566$ μm, so that $d_{\rm eff}=0.137$ μm, about half of the actual layer thickness d_a. Thus, it is clear that the depletion corrections in thin samples are extremely important for the correct calculation of n from the sheet concentration n_s. Because of this, it is worthwhile to check the value of n in such samples by capacitance-voltage (C-V) measurements, whenever possible.

When the electron beam is turned on, two immediate changes occur: (1) n increases, and (2) ϕ_s and ϕ_i decrease. Both phenomena occur because of electron-hole pair production by the beam. However, due to the short carrier lifetime, the increase of n in the neutral region ($d_{\rm eff}$) is negligible compared to the original n, 3×10^{17} cm^{-3}. On the other hand, for pairs created in the depleted regions, the existing electric fields will sweep holes to the surface (or interface) and neutralize negatively charged surface

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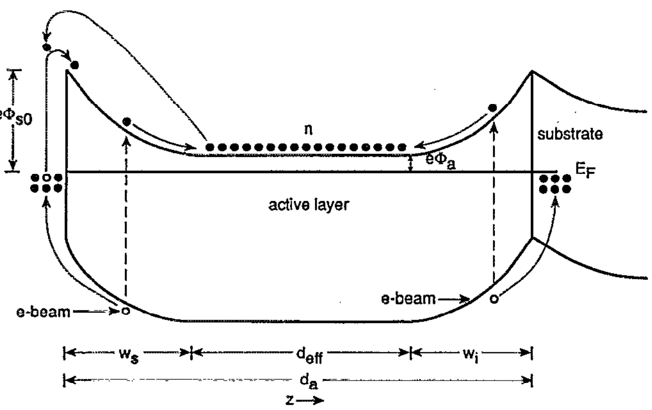

FIG. 1. An illustration of how charge transfers between the surface and bulk under electron irradiation. Here solid circles are free or bound electrons, and open circles, free or bound holes. The Hall effect measures only the neutral fraction (d_{eff}/d_a) of the layer.

(or interface) acceptor states. Thus, ϕ_s and ϕ_i will decrease, along with w_s and w_i (i.e., the band bending will be smaller).

In the numerical example given earlier, we assumed that $\phi_s \simeq \phi_i \simeq 0.7$ V. Although the value $\phi_s \simeq 0.7$ V is nearly always found for the oxidized GaAs surface, the magnitude of ϕ_i can depend on the substrate surface preparation before growth. In a previous study[6] we found that $\phi_i \simeq 0.95$ V, but *C-V* measurements on the present sample suggest a somewhat smaller value. Thus, it is probably not far in error, and much more computationally convenient, to approximate $\phi_i \simeq \phi_s \simeq 0.7$ V. Then, with the beam off (subscript "0")

$$n_0 = n_{s0} \Bigg/ \left[d_a - 2\sqrt{\frac{2\epsilon(\phi_{s0} - \phi_a - kT/e)}{en_0}} \right] \tag{3}$$

which along with Eq. (2) can be solved iteratively for n_0. With the beam on, n_0 remains the same, but n_s changes due to a change $\Delta\phi$ in ϕ_s. Thus,

$$n_0 = n_s \Bigg/ \left[d_a - 2\sqrt{\frac{2\epsilon(\phi_{s0} - \Delta\phi - \phi_a - kT/e)}{en_0}} \right]$$

or

$$\Delta\phi = \frac{e(n_s - n_{s0})}{8\epsilon} \left(2d_a - \frac{n_s + n_{s0}}{n_0} \right). \tag{4}$$

Note that although the assumption that $\phi_{i0} = \phi_{s0}$ with the beam off may be questionable, the beam-on values of ϕ_i and ϕ_s will be more nearly equal anyway, because a larger ϕ will be reduced more by virtue of its larger depletion volume (more "hole sweeping"). Thus, Eq. (4) should be fairly accurate, and since n_0 can be independently determined by *C-V* measurements as well as by Eq. (3), the assumption $\phi_{i0} = \phi_{s0}$ is not a serious problem.

To find $\Delta\phi$ as a function of sample parameters, we consider electron and hole flow to the surface acceptor states, of sheet concentration N_{ss}. The rate of change of N_{ss}^- with the beam off or on can be written

$$\frac{dN_{ss}^-}{dt} = -\nu_0 N_{ss}^- e^{-e\phi_{s0}/kT} + \frac{1}{e} A^* T^2 e^{-e(\phi_s - \phi_a)/kT} - \frac{I_b}{e} \frac{dE}{dz} \eta w_s, \tag{5}$$

where $\phi_s \simeq \phi_{s0} - \Delta\phi$. The first term on the right-hand side expresses the fact that the rate of emission of electrons from the surface states over the barrier into the semiconductor must be proportional to the number of charged surface states N_{ss}^- and to $\exp(-e\phi_{s0}/kT)$. Here, ν_0 is simply a proportionality constant. The second term, the opposite transition, is easily derived from the relationship $J_{m\to s} = en(0)v_z$, where $z=0$ is at the surface, and is known as the Richardson equation.[7] The third term is the change in N_{ss}^- due to the creation of electron-hole pairs by the beam. Here I_b is the beam current density; dE/dz is the energy lost by the beam, per unit length, due to e-h pair production; η^{-1} is the average beam energy lost in the creation of one e-h pair; and w_s is the surface depletion width which is important because we assume that all holes created in the region $0 \leqslant z \leqslant w_s$ experience the surface electric field and are swept to the surface states. This is a valid assumption because the sweep time will be less than 1 ps,[8] whereas the recombination time is typically about 1 ns. The preexponential factor ν_0 in the first term can be related to the beam-off ($I_b = 0$) values of N_{ss}^- and ϕ_s, namely, N_{ss0}^- and ϕ_{s0}:

$$\nu_0 = \frac{A^* T^2}{N_{ss0}^-} e^{e\phi_a/kT} \tag{6}$$

which is found by setting $dN_{ss0}^-/dt = 0$. We further note, from charge conservation and the definition of w_s, that $N_{ss}^- = (N_D - N_A) w_s \simeq n w_s$, and $N_{ss0}^- = n w_{s0}$, where the expressions for w_s and w_{s0} are given in Eq. (1). Finally, then, we set $dN_{ss}^-/dt = 0$ in steady state, with the beam on, to get

$$\Delta\phi = \frac{kT}{e} \ln \frac{w_s}{w_{s0}} \left(1 + \frac{w_{s0}}{K} e^{e(\phi_{s0} - \phi_a)/kT} \right), \tag{7}$$

where $K = A^* T^2 / I_b (dE/dz) \eta$. By combining Eqs. (1), (3), (4), and (7), K can be written in terms of known or measurable parameters:

$$K = \frac{[\frac{1}{2}(d_a - n_{s0}/n_0)] e^{e(\phi_{s0} - \phi_a)/kT}}{\left(\left(\frac{d_a - n_{s0}/n_0}{d_a - n_s/n_0} \right) \exp\left\{ \frac{e^2}{8\epsilon kT} (n_s - n_{s0}) [2d_a - (n_s + n_{s0})/n_0] \right\} \right) - 1}, \tag{8}$$

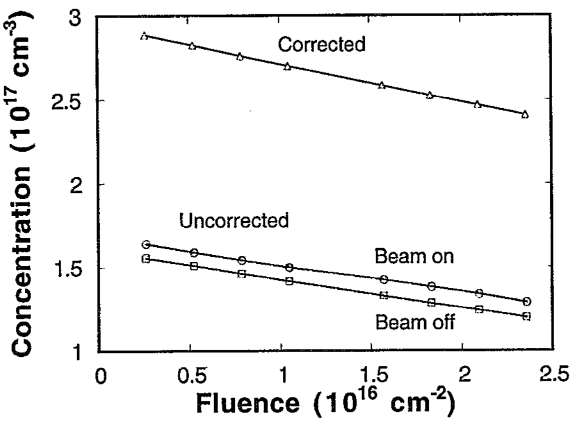

FIG. 2. Corrected and uncorrected carrier concentrations vs fluence for 1-MeV electron irradiation. The beam current densities were 0.155 μA/cm^2 for the first four points, and 0.333 μA/cm^2 for the last four points.

where n_s and n_{s0} are the sheet electron concentrations measured by the Hall effect with the beam on and off, respectively; n_0 is the volume electron concentration measured by C-V or by the Hall effect with the beam off [Eq. (1)]; and ϕ_a is given by Eq. (2).

RESULTS

The MBE sample, described earlier, was irradiated in air with 1 MeV electrons from a van de Graaff accelerator. Details of the apparatus are presented in a previous publication.[3] Hall-effect data (n_s) were gathered continuously during the irradiation, but at times the beam was turned off to get a value of n_0 by solving Eqs. (1) and (2) with $\phi_{s0}=0.7$ V. The beam-on value of n_s taken closest to a particular beam-off value of n_{s0} was used in Eqs. (7) and (8) to calculate $\Delta\phi$ and K, respectively. As the irradiation proceeded, n_0 decreased due to the net creation of acceptor defects by atomic displacement.[3] (However, most of the energy loss is still through electron collisions.) A plot of n_0 vs fluence, using two different beam currents, is shown in Fig. 2. As is seen, the uncorrected n_0 $[n_{s0}/d_a]$ is much smaller than the corrected n_0 $[n_{s0}/(d_a-2w_s)]$, which illustrates the problem of Hall-effect measurements in thin films.

From the known[9,10] free-surface potential ($\phi_{s0}\simeq0.7$ V) and the Hall data, we can calculate K from Eq. (8). From the first four points in Fig. 2, taken at $I_b=0.155$ μA/cm^2, we calculate an average $K=(1.62\pm0.14)\times10^5$ cm, and from the second four points ($I_b=0.333$ μA/cm^2), $K=(7.51\pm0.91)\times10^4$ cm. Also, from data (not shown) taken at $I_b=0.93$ μA/cm^2, $K=(2.62\pm1)\times10^4$ cm. Thus, KI_b is constant to within 4% over this beam current range, and gives confidence that Eq. (7) is correct. To determine A^*, it is also necessary to know dE/dz and η. By using the stopping power equations in Brandt[11] and mean excitation energies cited[12] in the ICRU Report No. 37, we get dE/dz $\simeq1.25\rho$ MeV cm^2/g$=6.65\times10^6$ eV/cm, where ρ is the density. (Here we have ignored charge state corrections which are estimated to be only a few percent.) Also, the quantity η has been measured[13] as 1 e-h pair/4.27 eV, and has been stated to be independent of the type of radiation to within 1%. Thus, we can calculate $A^*=0.44\pm0.05$ A/cm^2 K^2. Note that this result is not corrected for tunneling current. The tunneling correction parameter is $kT/E_{00}\simeq2.3$ (cf. Sec. III of Ref. 14) which means that tunneling is small but not negligible.

DISCUSSION

The theoretical value[7] of A^* for n-type GaAs is $4\pi em^*k^2/h^3\simeq8$ A/cm^2 K^2; thus, our determination of about 0.44 A/cm^2 K^2 seems anomalously low. However, it is rare to measure a value as high as 8 A/cm^2 K^2, and usually the numbers are much lower than that, even as low as 0.4 A/cm^2 K^2. For example, although Gol'dberg *et al.*[15] determined $A^*\simeq8.2\pm1.0$ A/cm^2 K^2 for the Schottky barrier Ni on n-type GaAs, Srivastava *et al.*[16] found that $A^*\simeq0.95$–1.64 for Au and 0.32–0.78 A/cm^2 K^2 for Al, and Missous and Rhoderick[14] in a very careful study determined that $A^*\simeq0.41\pm0.15$ A/cm^2 K^2 for Al on GaAs. Considerations of quantum-mechanical reflection at the interface and phonon scattering[17] can reduce the theoretical value of A^* to about 4 A/cm^2 K^2 but certainly not to 0.4. Thus, Schottky-barrier transport in GaAs is not well understood in terms of the present models. In our case, of course, we do not have a Schottky barrier, but a free surface. However, the method presented here can easily be extended to Schottky barriers, because the 1 MeV electrons will easily travel through the typically 1-μm-thick metallization with very little energy loss. (Note that the analogous excitation of e-h pairs by visible light would not work in this case because the light would be absorbed in the metal.)

It is also of interest to consider our method for the measurement of surface potential itself. That is, for some semiconductors, it may be that A^* is known much better than ϕ_{s0}, so that Eq. (8) can be used to determine a very accurate value of ϕ_{s0}, since it appears in an exponential term. Or, by using our present value of A^* for GaAs, we could determine the change in ϕ_{s0} as a result of various surface treatments on GaAs.

In summary, we have used the Hall effect along with a simple model to analyze depletion effects in the presence of a 1-MeV electron beam, and have determined a value for the Richardson constant A^*, which is within the range of values measured by others. The method should be easily extendible to Schottky barriers, with an advantage over present methods in that no current need be drawn through the barrier.

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[1] D. Pons and J. C. Bourgoin, J. Phys. C **18**, 3839 (1985).

[2] A. Meulenberg, H-L. A. Hung, K. E. Peterson, and W. T. Anderson, IEEE Trans. Electron Devices **35**, 2125 (1988).
[3] B. S. Ziebro, D. C. Look, J. W. Hemsky, and W. Rice, Rev. Sci. Instrum. **61**, 192 (1990).
[4] D. C. Look, C. E. Stutz, and K. R. Evans, Appl. Phys. Lett. **56**, 668 (1990).
[5] D. C. Look, *Electrical Characterization of GaAs Materials and Devices* (Wiley, New York, 1989), p. 46.
[6] D. C. Look, K. R. Evans, and C. E. Stutz, IEEE Trans. Electron Devices **38**, 1280 (1991).
[7] S. M. Sze, *Physics of Semiconductor Devices* (Wiley, New York, 1969), pp. 363–404.
[8] L. Min and R. J. D. Miller, Appl. Phys. Lett. **56**, 524 (1990).
[9] W. E. Spicer, I. Lindau, P. Skeath, and C. Y. Su, J. Vac. Sci. Technol. **17**, 1019 (1980).
[10] H. Shen, M. Dutta, L. Fotiadis, P. G. Newman, R. P. Moerkirk, and W. H. Chang, Appl. Phys. Lett. **57**, 2118 (1990).
[11] W. Brandt, Research Report, Radiation Physics Laboratory, E. I. du Pont and Co., Wilmington, DE (1960).
[12] ICRU Report No. 37, International Commission on Radiation Units and Measurements, Bethesda, MD (1984).
[13] J. E. Eberhardt, R. D. Ryan, and A. J. Tavendale, Nucl. Instrum. Methods **94**, 463 (1971).
[14] M. Missous and E. H. Rhoderick, J. Appl. Phys. **69**, 7142 (1991).
[15] Yu. A. Gol'dberg, E. A. Posse, B. V. Tsarenkov, and M. I. Shul'ga, Sov. Phys. Semicond. **25**, 266 (1991).
[16] A. K. Srivastava, B. M. Arora, and S. Guha, Solid-State Electron. **24**, 185 (1981).
[17] C. R. Crowell and S. M. Sze, Solid-State Electron. **9**, 1035 (1966).