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1997

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Technique for measurement of the minority carrier mobility with a bipolar junction transistor

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(Received 31 October 1996; accepted for publication 19 November 1996)

A simple technique to measure the minority carrier mobility using a bipolar junction transistor is demonstrated. By fixing the base-emitter voltage, the carrier injection into the base is constant. The collector current is then monitored as a function of a magnetic field applied perpendicular to the current transport across the base. The magnetic field leads to an increase in base transit time and a corresponding decrease in collector current. From the resulting fractional change in collector current, the minority carrier mobility in the base can be determined. For narrow base transistors, quasiballistic transport across the base must be taken into account when determining the bulk minority carrier mobility. © *1997 American Institute of Physics.* [S0003-6951(97)00904-2]

The minority carrier mobility is an important parameter for design of pn junction devices—but it is difficult to measure. Most minority carrier mobility measurement methods require the use of very high frequency modulation or ultrafast transient techniques. The two most common minority carrier mobility measurement techniques are the zero-field time-of-flight (ZFTOF)[1] and the short circuit unity gain cutoff-frequency (f_T)[2] techniques.

The ZFTOF technique utilizes an ultrafast laser pulse to generate an impulse function in time and space of electron-hole pairs at the top of the p region of a pn diode. (For measuring the minority hole mobility an np diode would be used.) The photogenerated electrons diffuse toward the junction and cause a current to flow when they are collected by the junction. The minority carrier diffusivity is obtained by fitting the measured transient response to the one-dimensional minority carrier diffusion equation. The ZFTOF technique requires ultrahigh-speed packaging and optimization of the diffusion region under the constraint that it be thin enough to minimize recombination effects yet thick enough to produce a measurable transit time.[1] The ZFTOF measurement is further complicated by photon recycling, optical generation of carriers with high excess energy, and optical generation of nonimpulse functions in space carrier profiles. The minority electron[3,4] and hole[5] mobilities in GaAs and the minority electron mobility[6] in InGaAs have been measured using the ZFTOF technique.

The minority carrier mobility in GaAs has also been determined by measuring the f_T of a bipolar junction transistor (BJT).[2,7] This method requires transistors with reasonable gains at low frequency, hence, homojunction BJTs in many semiconductor systems cannot be utilized for these measurements. At higher base doping levels the minority carrier lifetime in the base decreases, and thin bases have to be used to maintain the gain at low frequency, which leads to an increase in f_T. The application of this method to transistors with high base doping requires characterizing and de-embedding the effect of parasitics, which become significant at high frequencies.

A much simpler method to determine the minority carrier mobility from the change in base current with applied magnetic field in a heterojunction bipolar transistor (HBT) was demonstrated recently by Betser *et al.*[8,9] The Betser technique requires a HBT to eliminate back injection of holes from the base into the emitter. With a fixed emitter current, the applied magnetic field results in an effective increase in the base transit time, which is monitored by the corresponding increase in base current. From the change in base current with applied magnetic field, the minority carrier mobility in the base could be determined. Betser *et al.*[8,9] applied this technique to an InP/InGaAs HBT. We have modified the Betser technique so as to measure the change in collector current with the applied magnetic field, thereby eliminating the effect of processes such as back injection of holes and surface recombination, that also influence the base current. In this letter we demonstrate that the magnetotransport technique applied to collector currents can be used to determine the minority carrier mobility in any BJT, and so can be applied to any material system.

A schematic diagram of the experimental setup is shown in Fig. 1. The variation of collector current with magnetic

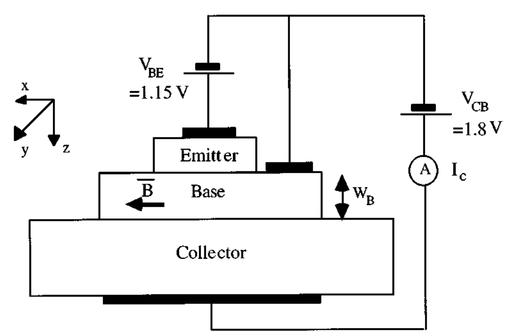

FIG. 1. Schematic diagram of the experimental setup. The fractional change in collector current is measured as a function of the intensity of the magnetic field applied perpendicular to the direction of current flow.

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field can be determined from the transport equation for electrons in the base of a BJT in the presence of a magnetic field as

$$J_{nz}=\frac{nq}{m^*}\left\langle\frac{\tau}{1+\omega_c^2\tau^2}\right\rangle\frac{\partial F_n}{\partial z}, \tag{1}$$

where q is the magnitude of electronic charge, J_{nz}, n, m^*, τ and F_n are the z directed components of current density, carrier concentration, electron effective mass in GaAs, momentum relaxation time and quasi-Fermi level for electrons in the base, respectively, and ω_c is the cyclotron frequency evaluated from

$$\omega_c=\frac{qB}{m^*}, \tag{2}$$

where B is the magnitude of the x directed magnetic field across the base. Assuming $\omega_c\tau\ll 1$, this can be written as[10]

$$J_{nz}=n\mu_n(1-\mu_n'^2B^2)\frac{\partial F_n}{\partial z}, \tag{3}$$

where μ_n and μ_n' are the minority carrier mobility and the magnetotransport mobility for electrons in the base. From Eq. (3) it is clear that the magnetic field reduces the effective diffusion constant in the base, and using standard BJT theory the collector current, I_c(B), under the applied base-emitter voltage bias, V_{be}, and magnetic field can be expressed as

$$I_c(B)=I_o(1-\mu_n'^2B^2)\exp\left[\frac{V_{be}}{k_BT}\right], \tag{4}$$

where I_o is the saturation collector current, k_B is the Boltzmann constant and T is the temperature of the electrons. One thus has

$$\frac{\Delta I_c(B)}{I_c(B=0)}=\mu_n'^2B^2, \tag{5}$$

where $\Delta I_c(B)$ is the reduction in the collector current caused by the magnetic field. By fixing the base-emitter and base-collector biases, the electron magnetotransport mobility can be determined from the resulting variation of $\Delta I_c(B)/I_c(B=0)$ with B.

The experimental technique for determining minority carrier mobility presented in this letter is analogous to the geometrical magnetoresistance (GMR) experiments[11] performed to determine majority carrier mobility. The magnetotransport technique measures a magnetotransport mobility and not the actual minority electron mobility. The ratio between these two quantities is similar to the ratio between the GMR mobility[10] and the majority electron drift mobility and can be expressed as[9]

$$\xi=\frac{\mu_n'}{\mu_n}=\sqrt{\frac{\langle(\tau(E))^3\rangle}{\langle\tau(E)\rangle^3}}, \tag{6}$$

where $\tau(E)$ is the momentum relaxation time of an electron with kinetic energy E. Betser *et al.*[11] estimated ξ using Eq. (6) for p-type InGaAs with $N_A=1.4\times10^{19}$ cm^{-3} and $N_A=3.4\times10^{19}$ cm^{-3} to be 1.195 and 1.315, respectively, at 300 K.

The fabrication process and the details of the films used for the GaAs BJTs have been described earlier.[12] The magnetotransport experiments were conducted at room temperature with constant base-emitter and base-collector voltages for BJTs with a base doping of 4×10^{19} cm^{-3} and base widths of 400, 200, 100 and 50 nm. The magnetic field was varied from 0 to 0.6 T and the variation of the fractional change in the collector current with the field intensity was measured. The data was fitted to Eq. (6) and the mobility was extracted from the slope of the fitted curve. The data and the best fit for the 100 nm base width transistor for V_{be}= 1.15 V and V_{cb}= 1.8 V are shown in Fig. 2.

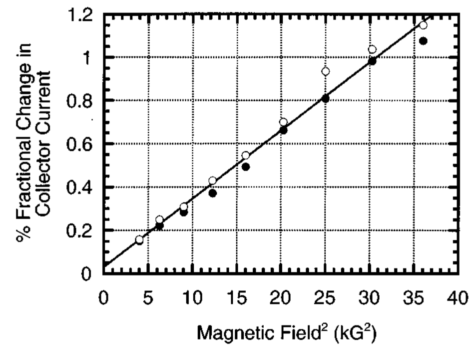

FIG. 2. Data and the best fit curve for W_B = 100 nm under bias conditions of V_{be}= 1.15 V and V_{cb}= 1.8 V. The empty and filled circles represent the data for positive and negative polarities of the magnetic field, respectively.

The measured mobility as a function of base width is shown in Fig. 3. The measured mobility decreases as the base width decreases, indicating quasiballistic transport across the thin bases.[12] To relate the measured mobility to the mobility in bulk material, the mobility versus base width data was analyzed using a device model based on a one-flux treatment of carrier transport proposed by Tanaka and Lundstrom,[13] from which the magnetotransport mobility in the base of a BJT was derived to be

$$\mu_n'(W_B)=\xi\left[\frac{\mu_B}{1+\dfrac{k_BT}{qW_Bv_R}\mu_B}\right], \tag{7}$$

where μ_B is the minority electron mobility in bulk material, W_B is the base width of the BJT, and v_R is the Richardson velocity evaluated from

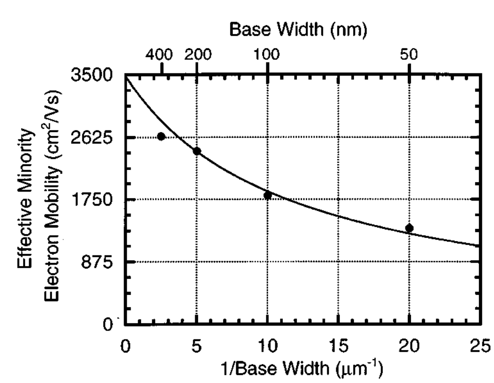

FIG. 3. Mobility vs reciprocal of base-width data and the best fit curve obtained from the Tanaka-Lundstrom model (Ref. 13).

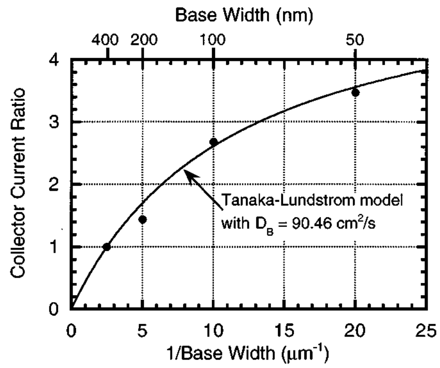

FIG. 4. Collector current ratio vs reciprocal of base-width data from the saturated collector current density experiments compared with that predicted by the Tanaka-Lundstrom model (Ref. 13) with the bulk electron diffusion constant = 90.46 $cm^2\ s^{-1}$ equivalent to a bulk minority electron mobility of 3480 $cm^2\ V^{-1}\ s^{-1}$.

$$v_R=(k_BT/2\pi m^*)^{1/2}, \tag{8}$$

where m^* is the effective mass of GaAs.

The fit of Eq. (7) to our experimental data is shown in Fig. 3 and gives a bulk minority carrier mobility of 3480 $cm^2\ V^{-1}\ s^{-1}$ assuming $\xi=1$. The ZFTOF technique yielded a mobility of 2885 $cm^2\ V^{-1}\ s^{-1}$ on similarly doped samples.[4] The discrepancy of 21% between the two techniques can be accounted for by a value of ξ within the range deduced by Betser *et al.*[9] for InGaAs and the error bar in the ZFTOF measurements.[4] The ratio of the collector current density versus base width predicted by Eq. (4) for μ_B = 3480 $cm^2\ V^{-1}\ s^{-1}$ is shown in Fig. 4.

We have modified the Betser *et al.*[8,9] magnetotransport technique for determining the minority carrier mobility in the base of a bipolar junction transistor. The uncertainty in the magneto transport factor for minority carriers (ξ) will influence the error associated with minority carrier mobility determined by this technique. For narrow base transistors, quasiballistic transport across the base must be taken into account to determine the bulk minority carrier mobility. We expect that this technique could be especially useful for characterizing base transport in devices whose functionality is critically dependent on processing, such as, graded base (compositional or doping) transistors. This technique can also be used to determine the base transit time. Therefore, for a transistor whose current gain is limited by base transport and whose base width is known, the minority carrier lifetime in the base could be determined from a measurement of the gain. From a measurement of the collector saturation current density, the $n_{ie}^2D_n$ product in the base could also be determined and n_{ie} extracted, where n_{ie} is the effective intrinsic carrier concentration in the base caused by heavy doping effects.[14] Therefore, with a single bipolar test transistor the minority carrier mobility, minority carrier lifetime, and effective intrinsic carrier concentration could be extracted.

This work was supported by the Office of Naval Research under Grant No. N00014-95-1-1302 and the NSF MRSEC for Technology Enabling Heterostructures under Grant No. DMR-9400415. The authors thank Professor R. F. Pierret for access to the equipment in the undergraduate semiconductor characterization laboratory.

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