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Dependence of Carrier Lifetime in InAlAs/InGaAs HEMTs on Gate-to-Source Voltage

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1. Introduction

High electron mobility transistors (HEMTs) made using the InAlAs/InGaAs material system have attracted much attention because of their high-speed operation and their applicability to high-speed ICs. Those HEMTs exhibit the frequency dependence of the drain conductance (G_d), which is a serious concern with regard to their use in high frequency circuits such as wideband analog and digital ICs. Holes are generated at the drain region through the impact ionization mechanism under a high electrical field and accumulate in the source region.[1, 2] Recently, it has been clarified that this frequency dependence arises from the recombination of holes accumulated in the source region with the 2DEG.[3, 4] In this case, the dominant mechanism is due to the Auger CHSH recombination process.[3, 4]

To satisfactorily understand our model, we have investigated the dependence of carrier lifetime τ on the effective drain-to-gate voltage ($V_{DG,eff}$), applied to the side of the gate-to-drain path, and on the gate-to-source voltage (V_{GS}) in detail.

2. Sample structure

The schematic structure of InAlAs/InGaAs HEMTs we used in this paper is shown in Fig. 1. The gate length and width of the HEMTs were 0.1 and 40 μm, respectively. The InGaAs channel layer was 15 nm thick. The barrier layer was InAlAs and the sheet density of the two-dimensional electron gas (2DEG) was 2 x 10^{12} cm^{-2}.

3. Experimental method

A network analyzer (HP8510B) with a frequency range of 45 MHz to 20 GHz was used for measuring the S-parameters. We obtained G_d from the real part of the Y22 parameter, which was transformed using the measured S-parameters. G_d can be understood by dividing it into two parts:[3, 4]

$$G_d(f) = G_{d0} + G_{d1}(f) \text{ and } G_{d1}(f) = G_{d10} \Big/ \sqrt{1+(f/f_{3dB})^2}, \quad (1)$$

where the second term G_{d1} (f) expresses Lorentz frequency dependence with f_{3dB} being the 3-dB-down frequency. The f_{3dB} is restricted by the carrier lifetime, τ, through the relation $1/2\pi\tau$.[3, 4] To confirm the validity of this physical model, we repeated the experiment as functions of $V_{DG,eff}$ and V_{GS}. For convenience, $V_{DG,eff}$, is defined as V_{DS}-$V_{DS,sat}$, where $V_{DS,sat}$ is the drain-to-source voltage defined in such a way that d^2I_{DS}/dV_{DS}^2 is at a minimum.[5)]

4. Results and Discussion

Figure 2 shows carrier lifetime τ as function of V_{GS} at several $V_{DG,eff}$'s. The concentration of holes generated by the impact ionization increases with V_{GS} because the concentration of 2DEG injected into the drain region increases with V_{GS} even if the multiplication rate does not change because of a fixed $V_{DG,eff}$. These holes recombine with electrons in the source region. As shown in the previous papers[3, 4], at the sheet hole concentration, p_s, excess of 10^{12} cm^{-2}, τ is dominated by the Auger recombination mechanism and decreases drastically as p_s increases. This is why τ decreases with V_{GS}. The 2DEG concentration, n_s, increases with V_{GS} via the well-known relation:

$$n_S = \frac{\varepsilon_s}{qd}\left(V_{GS} - V_{TH}\right), \quad (2)$$

where ε_s and d represent the dielectric constant and the effective thickness of the InAlAs barrier layer, respectively. Also, V_{TH} is the threshold voltage of HEMTs. In general, τ can be expressed as $\tau^{-1} = C_0 + C_1 p + C_2 p^2$, where C_0, C_1, and C_2 represent the coefficients for the radiative recombination, the bimolecular recombination, and the Auger recombination, respectively.[6)] Since the hole concentration multiplied by the impact ionization is proportional to the 2DEG concentration, p_s should be proportional to (V_{GS}-V_{TH}). In this experiment, therefore, τ can be written as

$$\tau^{-1} = C_0 + C_1(V_{GS} - V_{TH}) + C_2(V_{GS} - V_{TH})^2, \quad (3)$$

where C_0, C_1, and C_2 are newly defined parameters. As an example, Fig. 3 shows the result obtained using Eq. (3) at $V_{DG,eff}$ of 1.6 V. The value of the second term is much smaller than those of the first and the third terms. This implies that the radiative and the Auger processes are dominant in the recombination mechanism. Figure 4 shows the parameters deduced from Fig. 3 in the same manner. The coefficient C_0 is almost independent of $V_{DG,ef}$, as expected. On the other hand, the coefficient C_2 increases with $V_{DG,eff}$, implying that the Auger process is more dominant than the radiative one at a higher V_{DS}. This is because the electrical field on the drain side of the gate region is approximately proportional to $V_{DG,eff}$ and hence the ionization rate increases with $V_{DG,eff}$, i.e. the electrical field.[7)] The results mentioned above coincide well with those obtained in the previous paper.[4)]

According to theoretical result of Ref. 4, τ should decrease as increasing V_{GS}. The experimental result of τ, however, begins to saturate over V_{GS} of 0.4V as shown in

Fig. 2. To physically understand the above result, we have estimated theoretically the energy state and the carrier concentration profile for a system in which both electrons and holes co-exist by taking account of self-consistent solutions of both the Schrödinger and Poisson equations. In this theory, we modified the previous theory[4] and assumed that the ionized donors in the δ-doped layer capture electrons when the Fermi energy level lies close to the donor energy level. Concentration of ionized donors, N_d^+, is written as[7]

$$N_d^{\ +} = N_d \left[1 + 2\exp\left(\frac{E_f - E_d}{kT} \right) \right]^{-1} \tag{4}$$

where, N_d, E_f, E_d, k and T represent the concentration of donors, the Fermi level, donor level, the Boltzman constant, and temperature, respectively.

Figure 5 shows the theoretical result of the relationship between n_s and V_{GS}-$V_{TH.}$ If n_s follows Eq. 2, n_s is proportional to $V_{GS.}$ The result for this case is plotted with the dotted line for reference. As shown in Fig. 3, however, n_s tends to saturate over V_{GS} of 0.4V (corresponding to V_{GS}-V_{TH} of 0.7 V). When increasing V_{GS} greater than 0.3V, excess electrons are injected into the InGaAs channel through the source electrode and then subband energy levels of the channel are filled with electrons. In this case, excess electrons have the probability to penetrate into the δ-dope layer and to be captured by ionized donors in the δ-dope layer. As a result, the electric field of the δ-dope layer decreases and the potential energy profile including the surface and the δ-doped layer changes. This is why τ is saturated at V_{GS} greater than 0.4V.

Figure 6 is the energy band diagram for the conduction band and the carrier concentration of 2DEG, where V_{GS} is 0.47 V and the sheet electron density of 2DEG is 3.27×10^{12} cm^{-2}. The ve and ne represent the potential energy of the electrons and the electron concentration, respectively. The surface potential was assumed to be 0.6 V at equilibrium for convenience. The Fermi energy E_{fe} lies above the 2nd subband energy due to the high doping level and is close to the donor energy level. In this case, excess electrons exist in the δ-doped layer although most of electrons are distributed around the heterointerface on the side of InGaAs channel.

The fitting process made in Figs 3-4 must be modified using the theory mentioned above for a larger V_{GS}. The source resistance is not responsible for the phenomenon that τ is saturated at V_{GS} larger than 0.4V.

3. Conclusions

Form the experimental results on the V_{GS} dependence of the carrier lifetime τ, it was confirmed that the recombination of holes accumulated in the source region with the 2DEG is dominated by the Auger recombination process. Moreover, τ was found to saturate over V_{GS} of 0.4V. With increasing V_{GS}, excess electrons penetrate into the δ-dope layer and are captured by the ionized donors. This is the reason why τ is saturated at V_{GS} larger than 0.4V.

5. References

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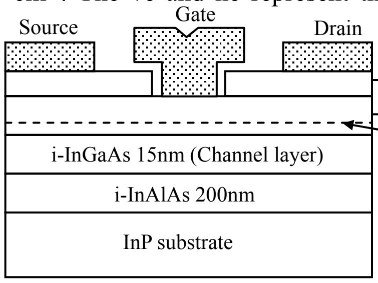

Fig. 1. Schematic cross sectional view of InAlAs/InGaAs HEMT.

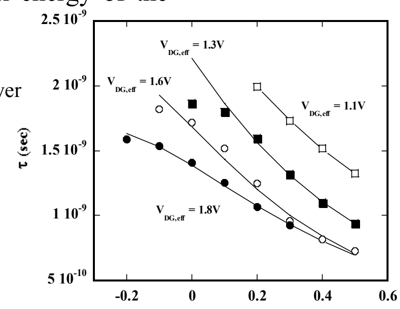

Fig. 2. Carrier lifetime τ as function of V_{GS} at several values of $V_{DG,eff}$.

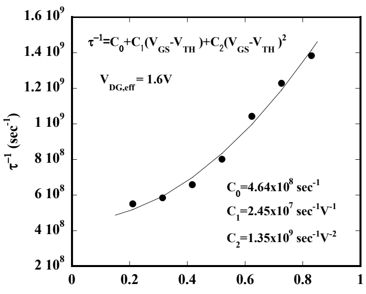

Fig. 3. τ^{-1} as function of (V_{GS}- V_{TH})

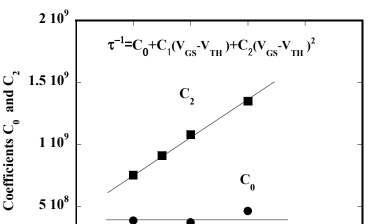

Fig. 4. Coefficients C_0 and C_2 as function of $V_{DG,eff}$.

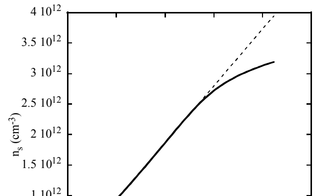

Fig. 5. Dependence of n_s as function of V_{GS}.

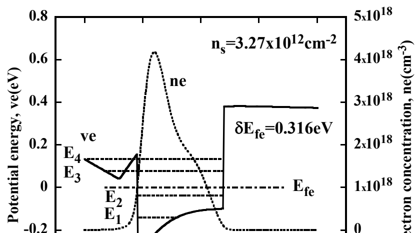

Fig. 6. The energy band diagram for the conduction band and the carrier concentration of 2DEG, where the sheet electron density of 2DEG is 3.27×10^{12} cm^{-2}.