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Auger Effect of Hole Accumulation on Characteristics of InAlAs/InGaAs HEMTs

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1. Introduction

High electron mobility transistors (HEMTs) made using InAlAs/InGaAs have attracted much attention because of their high-speed operation and their application in high-speed ICs. It has been demonstrated from the electroluminescence that holes are created in the drain region by impact ionization and that they drift toward the source due to the strong field across the channel and accumulate in the source region in InAlAs/InGaAs HEMTs.[1)] Optical irradiation on HEMTs also creates holes in the channel. Previous studies of the effects of optical irradiation on the characteristics of HEMTs revealed that the kink effect in InAlAs/InGaAs HEMTs is caused by a shift in the threshold voltage (V_{TH}), which arises from a change in the Fermi level due to an accumulation of holes in the source region.[2, 3)] At present, however, this problem is not understood well theoretically.

For a system where electrons and holes coexist in a quantum-well structure like HEMT's, we have calculated their energy state and potential profile by self-consistently solving the Schrödinger and Poisson equations for the first time. In addition, a comparison between the theoretical and experimental results is made for the shift of V_{TH} as a function of hole concentration. In this theory, the Auger process is taken into account as a recombination mechanism of carriers.

2. Sample structure

The schematic structure of InAlAs/InGaAs HEMTs we used in this paper is shown in Figure 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. Theory

The details of the theory and the calculation procedure are described elsewhere.[4, 5)] Account is also taken of the exchange-correlation energy between carriers to clarify the bandgap shrinkage effect. We estimated theoretically the energy state and carrier concentration for HEMT's of Fig. 1. The key parameter is the sheet concentration of holes that accumulate in the source region, p_s. The potential profile changes from the triangle to the square well as p_s increases above the sheet concentration of 2DEG because the same amount of electrons as holes are injected from the source to maintain the charge neutrality in the channel. As a result, the quasi-Fermi energy increases as p_s increases, leading to a decrease in the threshold voltage (V_{TH}).

The effective lifetime of holes, τ, is derived from averaging the generation rate of holes per unit time in the InGaAs channel. The CHSH process which includes two heavy hole bands (H), a conduction band (C), and an excited split-off band (S) was taken into account for the Auger recombination. We define τ as

$$\frac{1}{\tau}=\frac{1}{\tau_{Bn}}+\frac{1}{\tau_{CHSH}}\ ,$$

where

$$\frac{1}{\tau_{B_r}}\equiv\frac{\int_0^{L_z} B_r\left(n_{n0}(z)+\Delta p(z)\right)\Delta p(z)dz}{\int_0^{L_z}\Delta p(z)dz}$$

and

$$\frac{1}{\tau_{CHSH}}\equiv\frac{\int_0^{L_z} A_{sh}\left(n_{n0}(z)+\Delta p(z)\right)\Delta p(z)^2 dz}{\int_0^{L_z}\Delta p(z)dz}. \qquad (1)$$

Here, τ_{Br} corresponds to the lifetime for the radiative recombination and τ_{CHSH} to that for the Auger recombination. In addition, n_{n0} is the electron concentration at equilibrium and Δp is the excess hole concentration. Values of 4.4x10^{-28} cm^6s^{-1} and 4.6x10^{-10} cm^3s^{-1} were used for the coefficients A_{SH} and Br, respectively.

3. Experiment

The measurement was made using the system reported in Ref. 2. In this experiment the light from a semiconductor laser diode with an emission wavelength of 1.55 μm was illuminated from the backside of the substrate (the spot size of 20 μm). Light modulated in a square waveform at a frequency of 1 KHz was focused onto the transistor. The δV_{TH} synchronized with the incident light pulse was detected with a lock-in amplifier.

4. Results and Discussion

Figure 2 shows the p_s dependence of the change of threshold voltage, δV_{TH}, which varies approximately in proportion with p_s. Figure 3 shows the minority carrier lifetime, τ_{Total}, calculated taking account of the carrier distribution as a function of p_s. When p_s exceeds 10^{12} cm^{-2}, τ_{Total} is dominated by the Auger recombination mechanism and decreases drastically with increasing p_s.

The accumulation of holes at the source region can also be caused by irradiation of light onto the devices. Figure 4 shows the dependence of δV_{TH} (the symbol ●) on optical power P measured under the bias conditions of V_{gs}=0 V and V_{ds}=1.0 V. The measurement data deviated from the linear dependence on optical power beyond about 0.1 mW. Theoretically, P is defined as[6]

$$P = \frac{h\nu}{\eta} S \frac{p_s}{\tau}, \qquad (2)$$

where hν is the photon energy of the LD, η is the quantum efficiency, and S is the effective area irradiated with the LD. In Fig. 4, the theoretical result is illustrated with a solid line, η being 1.5 %. The dashed line represents the theoretical curve assuming a constant τ (~2 ns). The experimental result is consistent with the theoretical prediction.

4. Conclusion

Our experimental and calculated results prove that the change of threshold voltage, δV_{TH}, is caused by the accumulation of holes in the source region and their recombination with the 2DEG through the Auger recombination mechanism.

5. References

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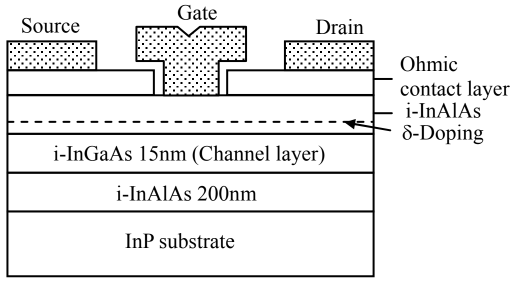

Fig. 1. Schematic cross sectional view of InAlAs/InGaAs HEMT.

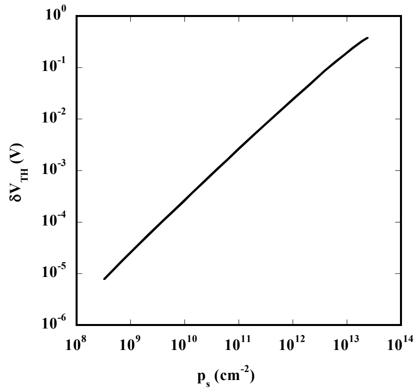

Fig. 2. The p_s dependence of δV_{TH}.

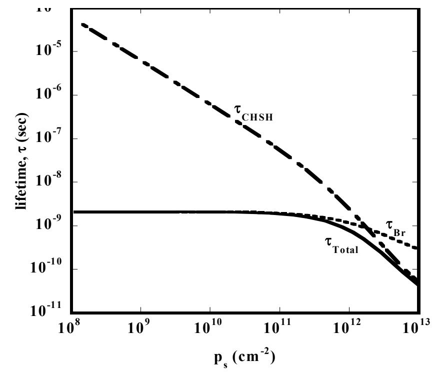

Fig. 3. Calculated minority carrier lifetime, τ_{Total}, as a function of the sheet concentration

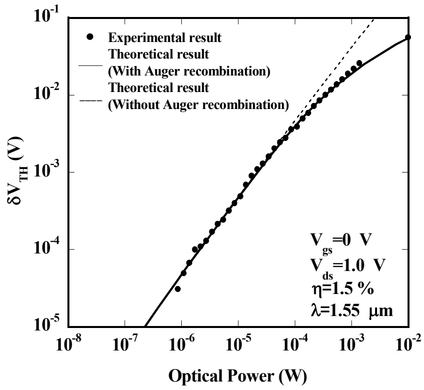

Fig. 4. The dependence of δV_{TH} on optical power P; the symbols ● correspond to the experimental results; the solid and dotted lines correspond to the theoretical results.