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Ultra-Fast Optical Response by InAlAs/InAs/InGaAs Pseudomorphic High Electron Mobility Transistors

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1. Introduction

High electron mobility transistors with a pseudomorphically strained InAs channel (InAs-PHEMTs) have superior electron transport properties and high electron density, which are due to a large conduction band discontinuity [1]. The current-gain cutoff frequency (f_t) of 628 GHz [2] and the maximum oscillation frequency (f_{max}) of 1.2 THz have been reported [1]. Recently, we have pointed out that the non-parabolicity of conduction band must be taken into account strictly when discussing the characteristics of HEMTs with the InAs channel [3]. In addition, we have demonstrated that these HEMTs can operate as not only a high speed transistor but an ultra-high speed optical receiver [4, 5]

In this work, we show the dependence of the optical response on the drain-to-source voltages (V_{DS}) for InAs-PHEMTs and make clear the physical mechanism for the response time. To physically understand those optical responses, we estimated the minority carrier lifetime τ using Auger recombination theory [6, 7]

2. Experiment

2.1. Device structure

We examined the pseudo-morphic channel of an InAs-PHEMT that was composed of the following layers: $In_{0.53}Ga_{0.47}As$ (2 nm), InAs (3 nm), $In_{0.7}Ga_{0.3}As$ (7 nm), and $In_{0.53}Ga_{0.47}As$ (6 nm) [8]. Figure 1 shows an InAs-PHEMT structure we used. Since a lower growth temperature is required to grow the strained layers, we grew the pseudomorphic HEMTs at 673 K.

2.2. Experimental setup

Figure 2 shows the experimental setup we used for measuring the optical response. In this experiment, the optical pulse from a fiber laser with an emission wavelength of 1.55 μm and a pulse width of 400 fs was illuminated from the backside of the substrate [4, 5].

3. Results and discussion

Figure 3 plots typical drain-current voltage characteristics for InAs-PHEMTs at room temperature (RT). Note that the figure indicates good pinch-off behavior, with the value of the threshold voltage (V_{th}) being about -0.35 V.

Figure 4(a) shows the optical response characteristics for InAs-PHEMTs at V_{GS} = 0 V for fourteen value of V_{DS}. A digitizing oscilloscope measures the transient characteristics of induced photocurrent by the change in output voltage through its 50-Ω input resistance (V_{out}.). The The V_{out} decreased exponentially but clearly have two gradients at V_{DS} of 1.4 V. Figure 4(b) shows the logarithmic plot of the result shown in Fig. 4(a) at V_{GS} = 0 V and V_{DS} = 1.4 V. The result clearly shows that the measurement data consist of two components whose lifetimes are different. Therefore V_{out} due to the optical response of the HEMTs can be expressed as; $V_{OUT} = A_1 \exp(-t/\tau_1) + A_2 \exp(-t/\tau_2)$ where A_1 and A_2 are constants.

Figure 5 shows τ_1 and τ_2 as functions of V_{DS}. Although τ_1 is almost constant at V_{DS} exceeding 0.8 V, it increases with decreasing V_{DS} below 0.7 V. On the other hand, τ_2 does not depend on V_{DS}. Holes photo-generated transit from the channel to the source under the channel field and accumulate at the source region [6, 7]. Electrons continue to transit across the channel toward the drain until a hole reaches the source and recombines with an electron there. In this case, the lifetime of electrons is given by the time for a hole to transit from the channel to the source region (τ_t) [9]. From the above considerations, we infer that (1) τ_1 is given by τ_t and (2) τ_2 is given by the Auger recombination lifetime (τ_A), which is discussed later, because it does not depend on V_{DS}. The reason why τ_1 increases with decreasing V_{DS} below 0.7 V is that the drift velocity of holes (v_d) is less than the saturated value (v_{sat}) and is proportional to the channel field. At V_{DS} exceeding 0.8 V, v_d of holes reaches v_{sat}.

The minimum value of τ_1 was 3.5×10^{-11} s. The distance for a hole to transit across the channel equals the gate length L_g (0.7 μm) and v_{sat} of holes is estimated to be 2.8×10^6 cm/s [10]. Using the above values, τ_t of holes was calculated to be about 3.0×10^{-11} s. This value agrees well with τ_1 determined experimentally at V_{DS} exceeding 0.8 V.

Next, we estimate the Auger lifetime (τ_A) using Fermi-Dirac statistics and the k-p band theory by Kane [11]. In InAs with the spin-orbit splitting energy comparable to the band gap, the Auger recombination including the process from the heavy hole band to the spin split-off band (CHSH process) is predominant [12]. However, the calculations done in Ref. [12] are based on Boltzmann statistics and hence are incorrect in the region where carriers degenerate. The transition rate (R) based on the CHSH process can be written [13] as;

$$R = 2\frac{2\pi}{\hbar}\left(\frac{1}{8\pi^3}\right)^3 \iiiint d^3\mathbf{k}_1 d^3\mathbf{k}_2 d^3\mathbf{k}_1' d^3\mathbf{k}_2' P|M|^2$$

$$\mathrm{x}\,\delta(E_1 + E_2 - E_1' - E_2')\delta(\mathbf{k}_1 + \mathbf{k}_2 - \mathbf{k}_1' - \mathbf{k}_2')$$

where $\mathbf{k_1}$ and $\mathbf{k_2}$ are the wave vectors of electrons in the conduction band (C), and $\mathbf{k_1}$'and $\mathbf{k_2}$' correspond to the wave vectors of holes in the valence band (H) and the spin split-off band (S). In addition, the net recombination can be obtained by subtracting the inverse process from the normal process. The details of the theory and the calculation procedure are described in Ref. 5. By letting Δn the injected carrier concentration, τ_A is defined as $\tau_A = \Delta n / R$.

Figure 6 shows the calculated results of τ_A as functions of the sheet hole concentration, p_s for five value of electron concentrations, n_0. As shown in the figure, τ_{CHSH} is $3.5\text{x}10^{-11}$ sec at $p_s = 3.0\text{x}10^{12}$ cm^{-2} and $n_0 = 2\text{x}10^{18}$ cm^{-3}, corresponding to the 2DEG concentration in InAs-PHEMTs. The theoretical result agrees well with the experimental one.

3. Conclusions

InAs-PHEMTs exhibited an ultra-fast optical response. The experimental results can be explained successfully using two different lifetimes, one being dominated by the time for a hole to transit from the channel to the source region under the channel field and the other dominated by the Auger recombination. To numerically understand the optical response, we estimated the minority carrier lifetime by using Auger recombination theory. The theoretical result agrees well with the experimental one.

References

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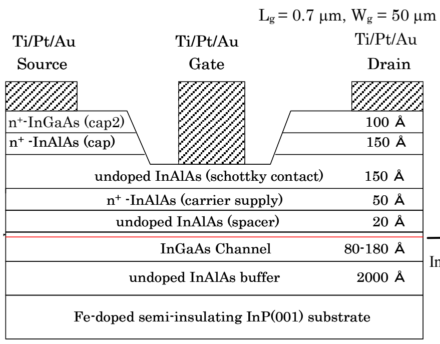

Figure 1 The InAs-PHEMT structure.

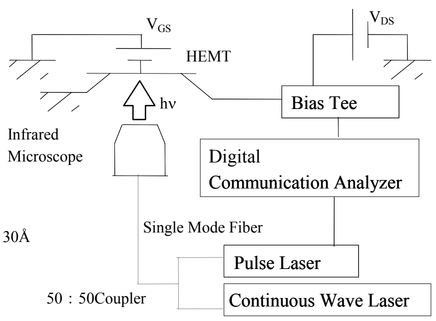

Figure 2 The experimental setup.

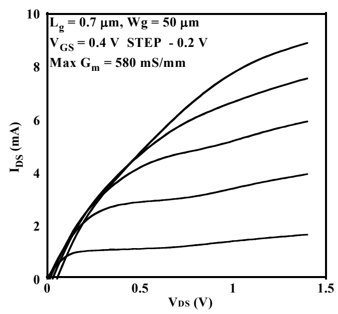

Figure 3 Typical drain-current voltage characteristics for InAs-PHEMTs at room temperature.

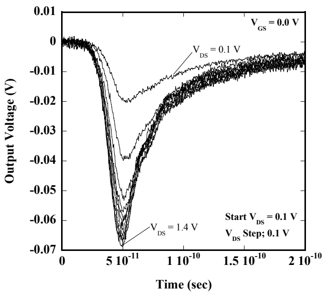

Figure 4(a) The optical response characteristics for InAs-PHEMTs at $V_{GS} = 0$ V for fourteen value of V_{DS}.

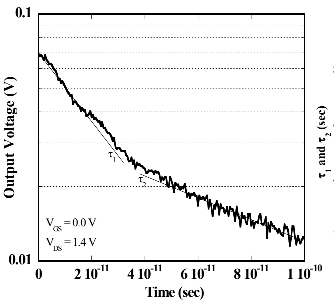

Figure 4(b) The logarithmic plot of the result shown in Fig. 4(a) at $V_{GS} = 0$ V and $V_{DS} = 1.0$ V.

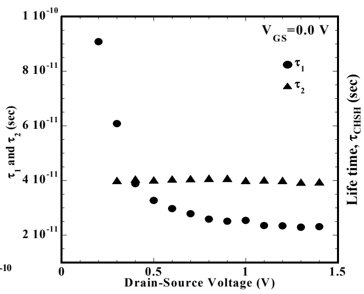

Figure 5 τ_1 and τ_2 as functions of V_{DS}.

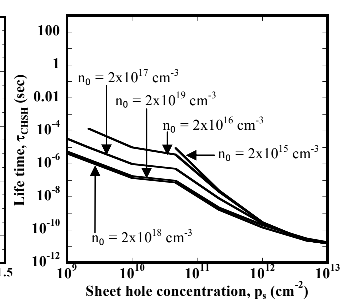

Figure 6 The theoretical result of τ_{CHSH} as functions of sheet hole concentration, p_s for five value of electron concentrations, n_0.