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Dependence of Optical Response Time on Gate-to-Source Voltage for InAlAs/InAs/InGaAs Pseudomorphic High Electron Mobility Transistors

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1. Introduction

InP-based high electron mobility transistors (HEMTs) have shown great success in microwave and millimeter applications. Especially, HEMTs 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 demonstrated that these InAs-PHEMTs can operate as not only a high speed transistor but an ultra-high speed optical receiver [3-5] In addition, we have shown the dependence of the optical response on the drain-to-source voltages (V_{DS}) for InAs-PHEMTs and have made clear the physical mechanism for the response time [6].

In this work, we show the dependence of the optical response on the gate-to-source voltages (V_{GS}) for InAs-PHEMTs. They exhibited an ultra-high optical response with a response time as low as 20 ps. To physically understand those optical responses, we estimated the minority carrier lifetime τ using Auger recombination theory [5, 6]

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) [4]. 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 [3, 4].

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 shows the optical response characteristics for InAs-PHEMTs at drain-to-source voltage, V_{DS} = 1.4 V for four values of V_{GS}. A digitizing oscilloscope measures the transient characteristics of induced photocurrent by the change in output voltage through its 50-Ω input resistance (V_{out}.). We have already shown in the previous papers [4, 6] that the V_{out} decreased exponentially and had two gradients, i.e. 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 τ_1 and τ_2 represent the lifetimes, A_1 and A_2 being constants.

Figure 5 shows τ_1 and τ_2 as functions of V_{GS}. As we have clarified from the V_{DS} dependence of measured lifetime [6], τ_1 is the time for a hole to transit the gate region (τ_t) and τ_2 the Auger recombination time (τ_A). In this figure, τ_1 and τ_2 decreased with decreasing V_{GS} and were saturated at V_{GS} less than -0.3 V. It is well-known from the device simulation that the electron velocity (v_e) increases with decreasing V_{GS} because of an increase in the channel field [7]. By the same reasoning, the hole velocity (v_h) also increases with decreasing V_{GS}. This is the reason why τ_t decreases with decreasing V_{GS}. According to our previous work in which the Schrödinger equations for electrons and holes were solved simultaneously [8, 9], the distributions for electrons and holes change depending on V_{GS} since the electrostatic potential profile under the gate region changes. At a higher V_{GS}, furthermore, electrons tend to distribute around the upper heterointerface and conversely holes around the lower heterointerface. At a lower V_{GS}, on the other hand, both electrons and holes coexist in the InAs channel. Therefore, the Auger recombination rate increases and hence the Auger recombination time decreases with decreasing V_{GS}. This is the reason why τ_A decreases with decreasing V_{GS}.

Next, we estimated the Auger lifetime (τ_A) using Fermi-Dirac statistics and the k-p band theory. The details of the theory and the calculation procedure are described elsewhere [4]. Figure 6 shows the calculated results of τ_A, the radiative lifetime (τ_R), and the total lifetime (τ_{Total}) as a function of the injected carrier concentration (Δn) at n_0 of $2\times10^{18}cm^{-3}$. Here n_0 corresponds to the average 2DEG concentration of the InAs channel [4]. Obviously, the Auger mechanism dominates the recombination process in InAs. Using the value of τ_A (1.8×10^{-11} s) experimentally obtained, it was found that the concentration of holes, accumulated in the source region, reaches as large as 2.8×10^{18}cm^{-3}.

4. Conclusions

InAs-PHEMTs exhibited an ultra-high optical response with a response time as low as 20 ps. The experimental results can be explained using two different lifetimes, one being dominated by the time for a hole to transit the channel under the channel field (τ_t) and the other dominated by the Auger recombination time (τ_A). The dependences of τ_t and τ_A on V_{GS} can be explained by the change of the channel filed and by the change of the distributions of electrons and holes, respectively. The minimum values of τ_t and τ_A was as low as 8.1×10^{-12} s and as low as 1.8×10^{-11} s, respectively. From the calculation using the Auger recombination theory, it was found that the concentration of holes, accumulated in the source region, reaches as large as 2.8×10^{18}cm^{-3}.

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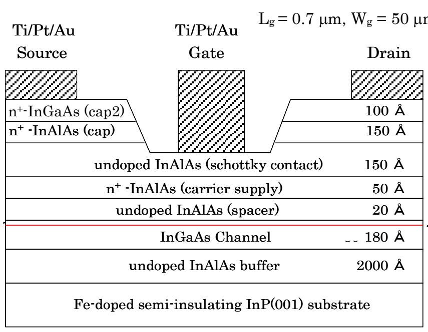

Figure 1 The InAs-PHEMT structure.

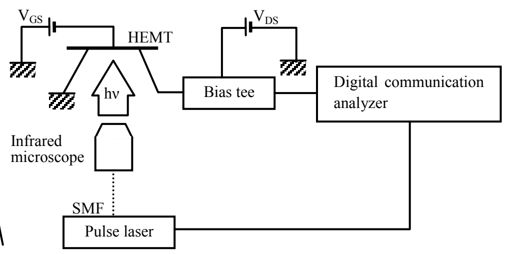

Figure 2 The experimental setup.

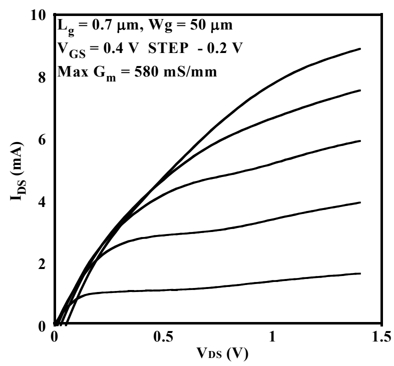

Figure 3 Typical drain-current voltage characteristics for InAs-PHEMTs at room temperature.

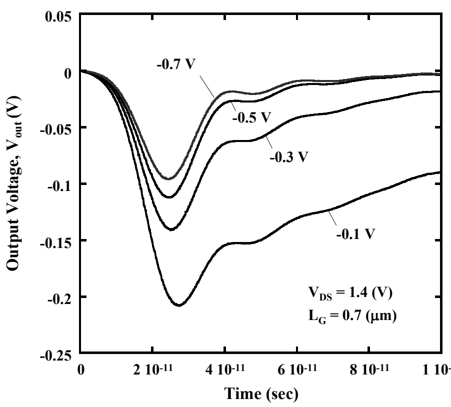

Figure 4 The optical response characteristics for InAs-PHEMTs at V_{DS} = 1.4 V for four values of V_{GS}.

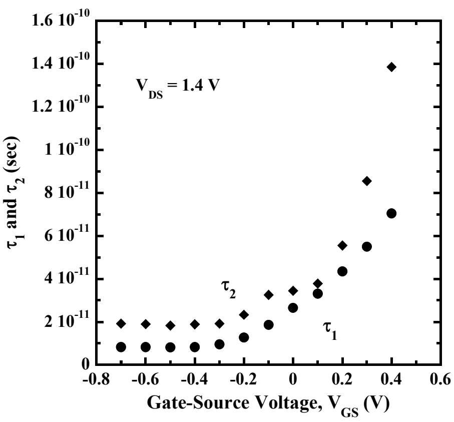

Figure 5 τ_1 and τ_2 as functions of V_{GS}.

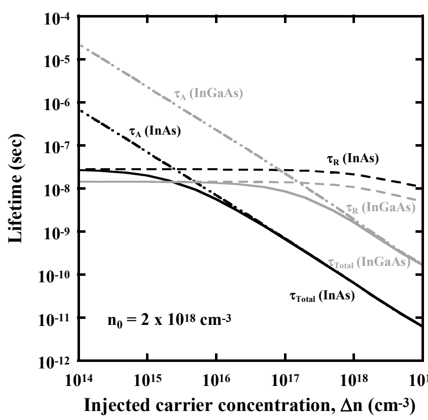

Figure 6 Theoretical results of the Auger lifetime τ_A, the radiative lifetime τ_R, and the total lifetime τ_{Total} as functions of the injected carrier concentration, Δn, at n_0 of 2×10^{18}cm^{-3}.