Influence of Hole Accumulation on the Source Resistance, Kink Effect, and On-State Breakdown of InP-Based HEMTs: Light Irradiation Study

Tetsuya Suemitsu, Hiroshi Fushimi, Satoshi Kodama, Satoshi Tsunashima, and Shunji Kimura
NTT Photonics Laboratories
3-1 Morinosato Wakamiya, Atsugi, Kanagawa 243-0198, Japan
Tel: +81-46-240-2795, Fax: +81-46-240-2872, Email: sue@aecl.ntt.co.jp

The influence of impact-ionized holes accumulating in the device was studied for InP-based InAlAs/InGaAs HEMTs using light irradiation experiments. Due to the small band gap of InGaAs, impact ionization occurs at relatively low bias voltages and generated holes tend to accumulate in the body of the device. We and some other groups reported the models in which the kink effect (an anomalous increase in the drain saturation current) is explained by hole accumulation [1,2]. In addition, we reported an improvement in the on-state breakdown voltage by the devices having a contact to extract holes [3]. However the hole accumulation is difficult to be estimated quantitatively because it depends on the generation rate (depending on bias conditions), recombination, and real space transfer of electrons and holes. Light irradiation is an alternative way to generate electron-hole pairs, and has an advantage that we can control the generation rate independently of the bias voltages by means of the incident light power. In this paper, we discuss the correlation between the source resistance, kink effect, and on-state breakdown by creating the hole accumulation by means of light irradiation.

Figure 1 shows the cross section of the sample device. The InP etch-stop layer was employed to control the threshold voltage of the device. The lateral depth of the gate recess was made about 120 nm by controlling the etching time for the cap layer. After that, the etch-stop layer was removed by wet-chemical etching to expose the InAlAs at the gate recess. Due to the carrier depletion caused by the large gate recess exposing InAlAs, the device exhibits a large kink effect without light irradiation as shown in Fig. 2(a).

When light with a wavelength of 1.48 μm, which is absorbed only in the InGaAs layer, was irradiated from the polished backside of the device, the DC characteristics of the device changed with the incident light power (P_{in}). The I-V characteristics of the device at a gate voltage of 0 V for various P_{in} from 0 to 90 μW are shown in Fig. 2(b). They indicate that the collapsed drain current is recovered (i.e., the kink effect is suppressed) with an increase in P_{in}. In a previous paper, we modeled the kink effect by the modulation in the source resistance caused by ionized holes accumulated in the gate recess region [1]:

$$I_d \approx \frac{g_{m0}(V_{gs}-V_{th})}{1+g_{m0}R_{s0}+g_{m0}R_{recess}} \approx \frac{(V_{gs}-V_{th})}{R_{recess}} \approx \frac{q\mu(V_{gs}-V_{th})}{L_{side}}n_{ss}, \text{ and } n_{ss} \approx n_{ss0} + \frac{\varepsilon k_B T}{q^2 d}\ln\left(1+\frac{\Delta p}{p_0}\right) \text{ (when } R_{recess} >> R_{s0}), \quad (1)$$

where R_{recess} is the resistance of the gate recess region, R_{s0} is the rest of the source resistance, n_{ss} is the electron concentration in the gate recess, n_{ss0} is n_{ss} without irradiation, Δp is the increase in the hole concentration due to impact ionization.

Since the light irradiation causes the hole accumulation independently of the bias condition, this experiment enables us to directly observe the correlation between the hole accumulation and the source resistance (R_s). Under the light irradiation, R_s was measured by the end-resistance method [4]. The R_s decreased dramatically from 5.4 to 1.3 Ω.mm by illuminating at the minimum power (0.6 μW), and further decreased with increasing light power (Fig. 3). Assuming that R_{s0} is constant, we calculated the inverse of R_{recess} ($1/R_{recess} \propto n_{ss}$) and plotted it as a function of P_{in} (Fig. 4). The drain current (I_d) at V_{ds} = 0.5 V (i.e.,'pre-kink' region) versus P_{in} is also shown in the figure. The increase in I_d is primarily explained by the increase in n_{ss} at low P_{in} (< 10^2 μW). This result supports the model that the modified R_s causes the kink effect. At higher P_{in}, however, I_d is boosted more than n_{ss} is. As shown in Fig. 4, the P_{in} dependence of I_d can be fitted by

$$I_d = I_{d0} + A\ln\left(1+\frac{P_{in}}{P_0}\right) + BP_{in}, \quad (2)$$

where I_{d0} is the dark current, and A, B, and P_0 are fitting parameters. Since the hole concentration is proportional to P_{in}, the second term of (2) is regarded as the increase in I_d due to the kink effect. The third term of (2) increases linearly with the hole concentration and becomes significant at large P_{in} (> 10^2 μW). Another important phenomenon observed at large P_{in} is the negative shift in the threshold voltage (V_{th}) as shown in Fig. 5. The linear increase in I_d in (2) is explained by the shift in V_{th} caused by the hole accumulation under the intrinsic gate region, which is modeled by

$$V_{th} = V_{th0} - \frac{q}{\varepsilon}pd_{hole}, \quad (3)$$

where V_{th0} is the threshold voltage without irradiation, p is the hole concentration under the gate region, and d_{hole} is the effective distance from the gate to the accumulated holes. The negative shift in V_{th} requires a larger hole concentration than the kink effect, and the resulting increase in I_d is more significant than the kink effect. In actual devices, therefore, the increase in I_d caused by the shift in V_{th} is regarded as the on-state breakdown, which is another phenomenon caused by impact ionization. This suggests that we can improve the on-state breakdown voltage by suppressing the hole accumulation in the gate region. Figure 6 shows results of a two-dimensional numerical analysis of 0.1-μm-gate HEMTs with two lifetimes of holes in the InGaAs channel, namely, 1 ps and 10^3 ps. The longer lifetime, which means a larger hole concentration, gives an explosive increase in I_d at lower drain voltage. This also supports the influence of hole accumulation on the on-state breakdown.

[1] T. Suemitsu, T. Enoki, N. Sano, M. Tomizawa, and Y. Ishii, IEEE Trans. Electron Devices, vol. 45, pp. 2390, 1998.
[2] M. H. Somerville, J. A. del Alamo, and W. Hoke, IEEE Electron Device Lett., vol. 17, pp. 473, 1996.
[3] T. Suemitsu, T. Enoki, and Y. Ishii, Electron. Lett., vol. 31, pp. 758, 1995.
[4] K. Lee et al., IEEE Trans. Electron Devices, vol. 31, pp. 1394, 1984.

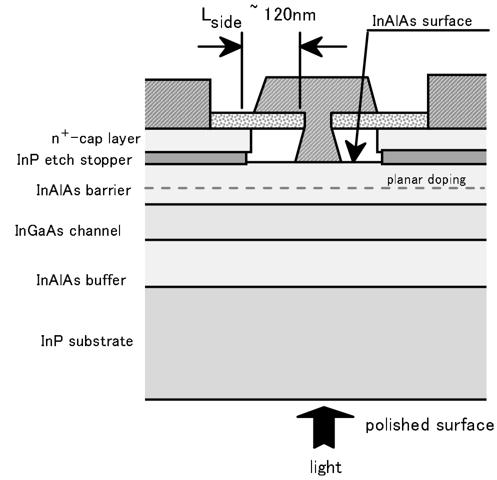

Fig. 1: Schematic cross section of sample InP-based HEMT. Gate length is 0.1 µm. Backside of the InP substrate was polished for light irradiation study.

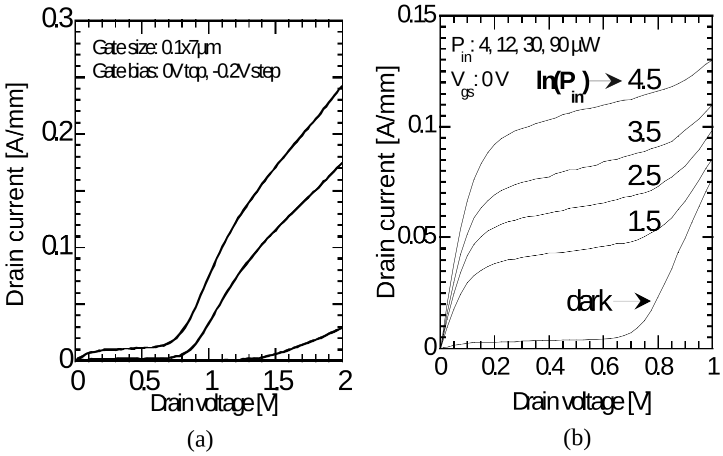

Fig. 2: (a) Typical I-V characteristics of the HEMT without light irradiation. (b) Change in drain current at a constant gate voltage (0 V) induced by light irradiation. The incident light power (P_{in}) was varied from 0 to 90 µW.

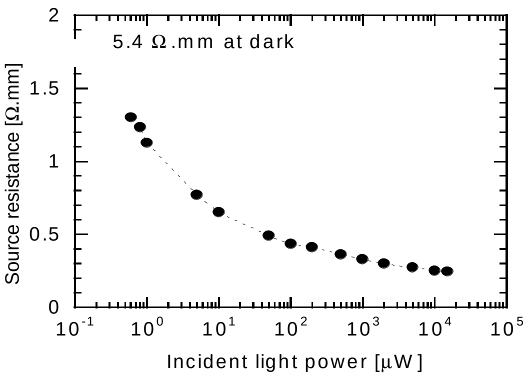

Fig. 3: Source resistance versus incident light power. Source resistance was measured by the end-resistance method.

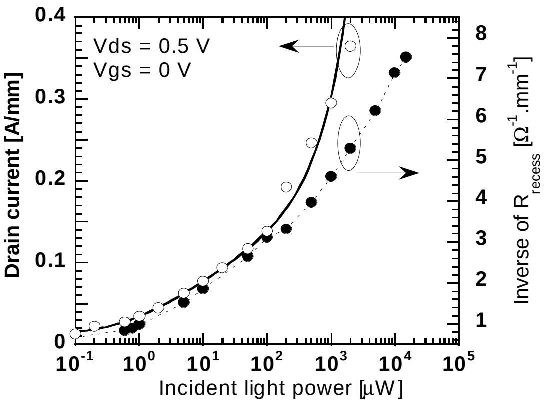

Fig. 4: Drain current and the inverse of gate recess resistance ($1/R_{recess}$) versus incident light power. Drain current agrees with (2) by appropriate fitting parameters. Gate voltage and drain voltage are fixed at 0, and 0.5 V, respectively.

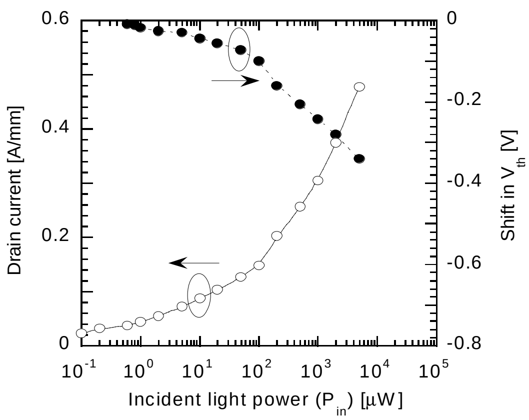

Fig. 5: Drain current and the shift in the threshold voltage of a HEMT versus incident light power.

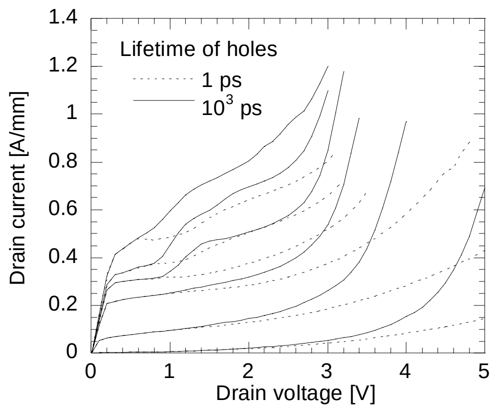

Fig. 6: Numerical analysis of I-V characteristics of a InP-based HEMT [1]. Different lifetimes of holes in InGaAs channel (1 and 10^3 ps) lead to different on-state breakdowns. Gate voltages: 0.2 V top, -0.2 V step.