Dynamic Simulation of Multiple Trapping Processes and Anomalous Frequency Dependence in GaAs MESFETs

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Frequency dependent characteristics of GaAs MESFETs due to deep traps are one of the most serious problems in achieving high device performance. In this study, mechanisms of frequency dependent transconductance Gm and output resistance Rd are unifyingly revealed by incorporating dynamics of quasi-Fermi levels. Multiple frequency dispersions of Gm and Rd, and pulse narrowing phenomena due to electron and hole traps are demonstrated using hydrodynamic transport theory and a Schokkley-Read-Hall type deep trap model, where rate equations associated with multiple trapping processes are analyzed self-consistently. It is also found that there exist spatial and time effects of multi-traps on the dispersion characteristics.

First, hysteresis in current-voltage characteristics due to deep traps and dynamics of quasi-Fermi levels are shown schematically in Fig. 1. As shown in (a), when Vg is applied at a low frequency, the ionized deep donors cause a large current due to channel widening at high Vg. For a high frequency Vg, however, the occupation ratio of the deep donors cannot change rapidly enough, so Gm decreases. A similar decrease in Gm may also be caused by deep acceptors. The lowering of the quasi-Fermi levels with increasing Vg, therefore degrades Gm at high frequencies. Equivalently, (b) shows that the rise of the quasi-Fermi levels with increasing Vd degrades Rd at high frequencies.

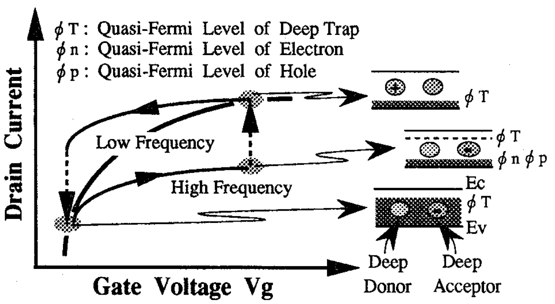

Fig. 1 (a) Hysteresis of Current-Voltage Characteristics in Gate Lag

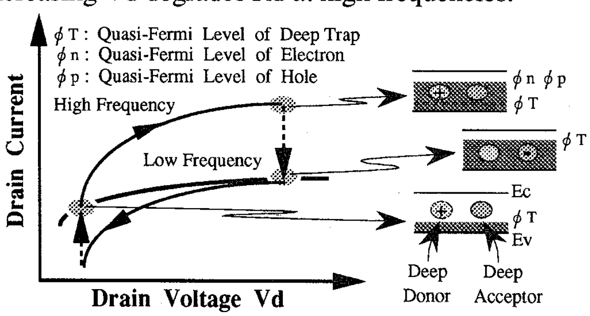

Fig. 1 (b) Hysteresis of Current-Voltage Characteristics in Drain Lag

There are two mechanisms for lowering quasi-Fermi levels with increasing Vg. One is hole injection from the Schottky gate electrode and the other is electron depletion due to reverse bias on the pn junction between substrate and n channel. On the other hand, electron injection and hole depletion in the substrate correspond to two mechanisms of rising quasi-Fermi levels with increasing Vd. Because the occupation ratio of deep traps changes dramatically as the quasi-Fermi levels cross the trap levels, the frequency dependent characteristics can be ascribed to the mechanisms as summarized in Table 1. Utilizing this classification, deep traps can be identified by the correlation between characteristics observed experimentally. For example, it is shown that hole traps in the substrate induce both Gm enhancement and Rd degradation in the high frequency domain.

Table 1 Mechanisms of Frequency Dependent Characteristics in Forward Bias Related to Deep Traps

Deep Trap	Transcondcutance	Output Resistance
Hole-Trap near the Surface	Hole Injection From the Schottoky Gate Electrode ↓	Hole Depletion due to Reverse Bias ↓
Hole-Trap in the Substrate	Hole Depletion due to Reverse Bias ↑	Hole Depletion due to Reverse Bias ↓
Electron-Trap near the Surface	Electron Injection From the Source Electrode ↑	Electron Injection From the Source Electrode ↓
Electron-Trap in the Substrate	Electron Depletion due to Reverse Bias ↓	Electron Injection From the Source Electrode ↓

(↑ : Enhancement, ↓ : Degradation in High Frequency Domain)

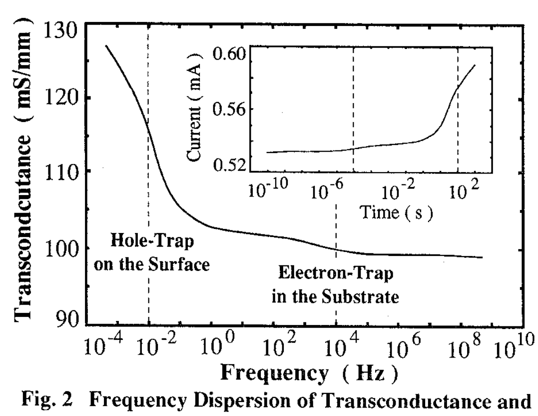

Fig. 2 Frequency Dispersion of Transconductance and Transient Current in Response to a Step Bias

According to the present theory, it is found that frequency dependent characteristics of GaAs MESFETs are mainly caused by three kinds of deep traps : 0.75 eV hole-trap acceptor on the surface, 0.75 eV electron-trap donor EL2 and 0.45 eV electron-trap donor in the substrate. Figure 2 shows the frequency dispersion of Gm and transient current in response to a step change in Vg. It can be seen that the transient current increases in two time domains. The large increase after 10^{-2} s is due to hole capture of the surface state and the slight increase of about 10^{-4} s is due to electron emission of the 0.45 eV bulk trap. EL2 is also likely to increase the current after 10^{-2} s due to the same process. However, the EL2 concentration is generally much lower than the surface state density, so EL2 becomes of no importance. It is also demonstrated that multiple frequency dispersions of Gm occur due to these traps, where characteristics at frequency $1/\Delta t$ can be evaluated from the increase in transient current ΔI at time $\Delta t/2$ divided by voltage modulation ΔV. Furthermore, transient current in response to a pulse modulation of about 10^{-2} and 10^{4} Hz are shown in Fig. 3 (a) and (b), respectively. Both responses show pulse narrowing phenomena caused by charging and discharging of deep traps and the decrease in current amplitude compared with the ideal response indicates the degradation in Gm at high frequencies. It should be noted that frequency dispersion of Gm using the step bias deviates less than 5% from that resulting from the pulse modulation, therefore dispersion characteristics can be analyzed by transforming the transient current in response to the step bias.

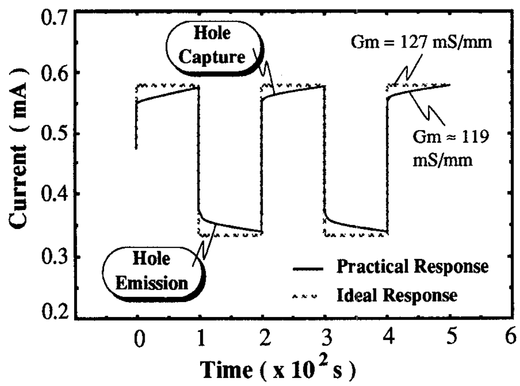

Fig. 3 (a) Pulse Narrowing due to Hole-Trap on the Surface

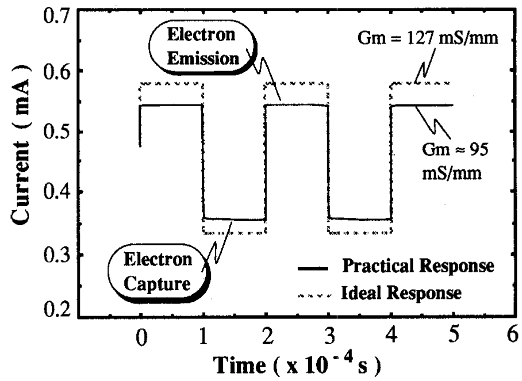

Fig. 3 (b) Pulse Narrowing due to Electron-Trap in the Substrate

Frequency dispersions of Rd are shown in Fig. 4. It is found that the electron-traps with different levels in the substrate cause the multiple frequency dispersions which indicate the time multi-trapping effect. Furthermore, both Rd and decrease in Rd at high frequencies become larger as surface state density increases. This is because the ratio of current modulation by charging processes of electron-traps becomes larger as the surface state extends depletion regions and decreases the current modulation by Vd. Consequently, although frequency dispersions of Rd are not associated with the surface state, the decrease in Rd at high frequencies is actually dependent on surface state density, which shows the spatial multi-trapping effect.

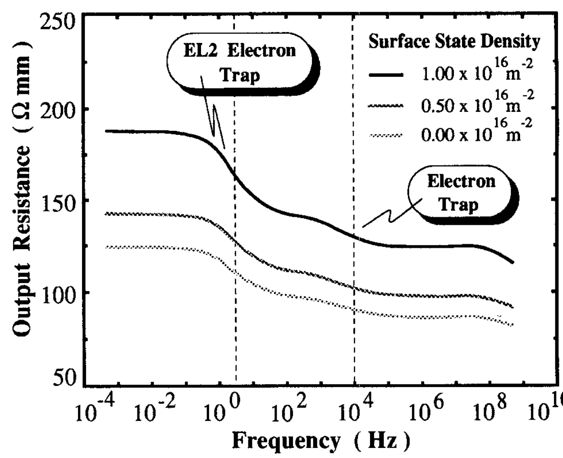

Fig. 4 Multiple Frequency Dispersions of Output Rsistance

To summarize, mechanisms of frequency dependent Gm and Rd are unified by incorporating the dynamics of quasi-Fermi levels. Multiple frequency dispersions of Gm are caused by the surface state due to hole injection from the Schottky gate electrode and by the bulk trap due to electron depletion with increasing gate voltage. Multiple frequency dispersions of Rd are also caused by the bulk trap and EL2 due to electron injection with increase in drain voltage. Although Rd dispersion is not caused by the surface state, it can be shown that the difference between static and dynamic characteristics of Rd becomes larger as surface state density increases.