Advanced Quasi-Self-consistent Monte Carlo Simulations on High-Frequency Performance of Nanometer-scale GaN HEMTs Considering Local Phonon Distribution

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***Abstract*— As a means of investigating both the electrical and thermal properties in nanometer-scale electron devices within a reasonable computing time, we previously proposed a quasi-self-consistent Monte Carlo simulation method, including spatially dependent electron-phonon scattering rates, and a replica technique for phonon generation which enable us to calculate long-time phonon transport. Using this advanced Monte Carlo method, we succeeded in simulating the high-frequency characteristics of nanometer-scale gallium-nitride high-electron-mobility transistors (HEMTs). The simulations suggest that a shorter gate HEMT exhibits larger performance degradation in cut-off frequency due to the local-heating effect. We also report Monte Carlo simulations of nm-scale GaN HEMTs with heat-removal structures on the surface.**

Keywords—Monte Carlo; device simulation; electron transport; phonon transport; High Electron Mobility Transistor (HEMT); Gallium Nitride (GaN)

I. INTRODUCTION

Next-generation power-semiconductor devices are required due to the recent developments in power electronics. Gallium nitride is a promising material for high-frequency, high-power, and low-loss devices as it has wider bandgap, higher breakdown voltage, and higher saturation velocity. Heat generation is a serious problem because power devices are operated at a large-current and high-voltage regime. For the purpose of analyzing and designing non-stationary electrical and thermal phenomena in nanoscale devices, a self-consistent Monte-Carlo simulation method, in which electron transport and phonon transport can be simulated microscopically and simultaneously by using the particle method, must be useful and accurate [1]. However, it consumes many resources and has not been used to study realistic transistors with a sufficient degree of convergence. Conducting a self-consistent simulation in a realistic amount of time is difficult because of the large difference between the time scales of the electron and phonon-transport phenomena. We previously proposed the “Quasi Self-consistent Monte Carlo method” [2, 3] as a solution to this computing problem by introducing different time increments for the electron and phonon transports and a new algorithm of a replica technique for phonon generation map (Fig. 1). We also modified the simulation model for calculating electron/phonon-scattering rates directly from a local number of phonon particles emitted by hot electrons instead of estimating local temperature [4], which consumes more computer resources and is less accurate. In this study, we applied this new method to simulate the high-frequency characteristics of GaN HEMTs.

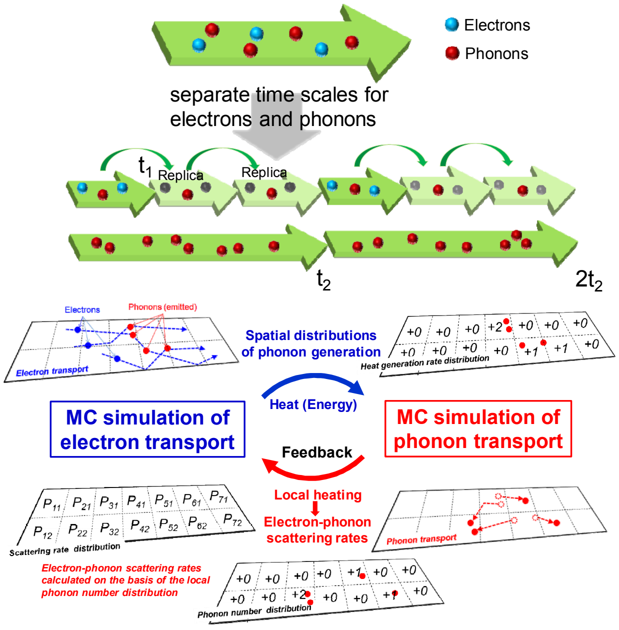
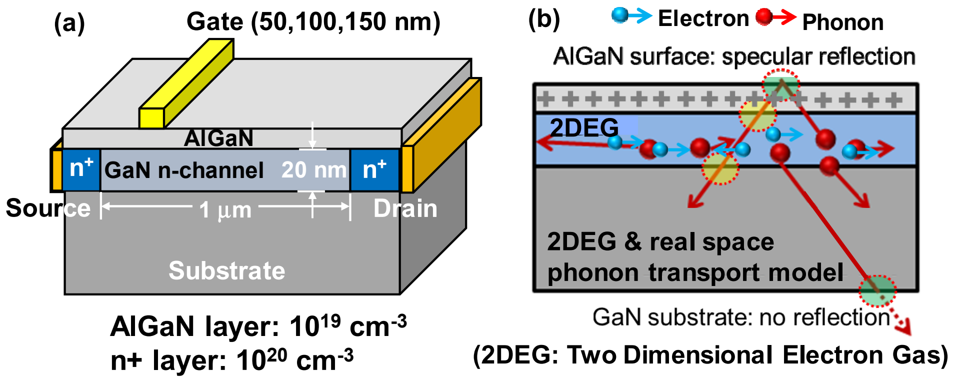


Fig.1 Schematic diagram of quasi self-consistent simulation procedure for electron and phonon transport [2-4]



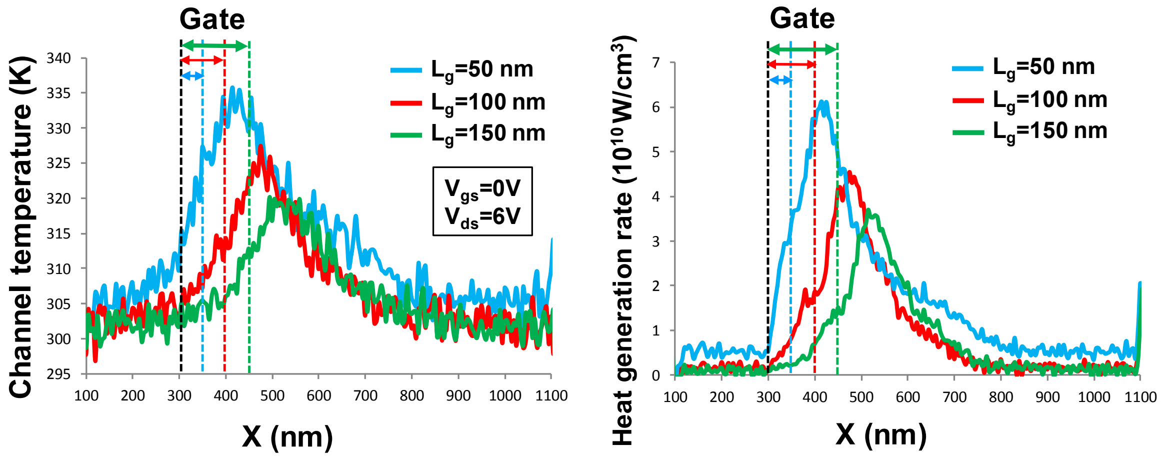
Figs.2 Two-dimensional AlGaN/GaN HEMT model and boundary-reflection models for electrons and phonons

II. SIMULATION METHOD

Figs. 2 (a) and (b) show a two-dimensional AlGaN/GaN-HEMT model and boundary conditions for electron and phonon transport at the boundaries and hetero-interfaces. Detailed information about the model structure and electron/phonon-scattering models were given in a previous study [4]. The gate lengths (Lg) are 50, 100, and 150 nm, and the total number of electron particles in the model (Qtotal), varies due to bias conditions. The model is implemented by placing the n-channel region on the outer edge of the source/drain n+ region, where electron particles are supplied to and/or absorbed from the device.

III. RESULTS AND DISCUSSIONS

Figs. 3 shows the simulated local-channel temperature and heat generation rate profiles of 50, 100, and 150 nm-gate HEMTs. The drain-to-source voltage (Vds) and gate voltage (Vgs) were 6 and 1 V, respectively. We estimated the local temperature by using the Bose-Einstein distribution in the same way as in our previous model [2, 3]. The peak temperature of 50 nm-gate HEMT was 35ºC higher than room temperature. Note that the positions of the local-temperature peaks were about 70 nm closer to the drain than the drain-side edge of the gate. This difference is due to the drift effect during the mean free time of the electron-phonon scattering with phonon emission.



(a)

(b)

Figs.3 Profiles of local channel temperature (a) and heat generation rate (b) in nm-gate AlGaN/GaN HEMTs

The unity-current gain cut-off frequency (f_T) can be expressed as

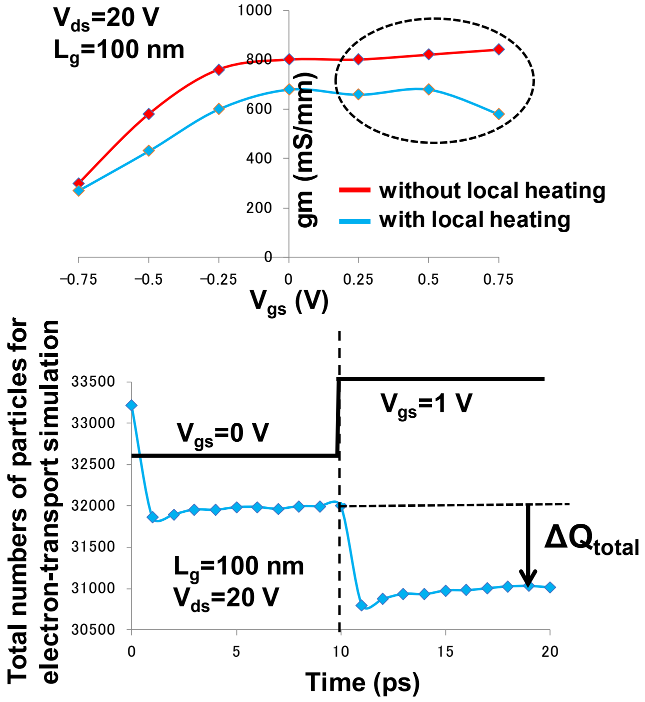
$$f_T=gm/2\pi C_{gs}$$

where gm and C_{gs} are transconductance gate-source capacitances The C_{gs} is estimated by

$$C_{gs} =\Delta Q_{total}/V_{gs},$$

where ΔQ_{total} can be obtained from the total number of particles (electrons) in the device model. For example, the V_{gs} dependence of transconductance and the change in Q_{total} by changing the applied V_{ds} from 0 to 1 V are shown in Fig. 4 at a drain voltage of 20 V in the 100-nm-gate HEMT. Note that degradation by local heating in gm was evident, as predicted, and this effect became larger at a higher V_{gs} regime (which means a larger drain-current regime). Figure 5 also shows the L_g dependency of f_T, including an experimental data [5] at a drain voltage of 6 V. It is clearly shown that f_T also degraded due to local heating, and this effect increased when L_g was shorter, which means that more hot electrons are generated and local heating is accelerated in shorter L_g devices.

Heat-removal technologies have more important for developing high-performance high-power amplifier (HPA) modules. Fig. 6 shows an advanced heat-removal structure of a flip-chip HEMT HPA [6], where a vertically aligned carbon nanotube bundle [6-8] is used as a thermal bump and a carbon nanotube forest is used as a thermal interface materials (TIM). Nano-carbon composite materials, such as graphene multi-layers combined perpendicularly with aligned carbon nanotubes, which Kondo et al. discovered in 2008 [8], should be most suitable for such structures. We used our Monte Carlo simulation method to simulate a 50-nm-gate-AlGaN/GaN HEMT with heat-removal structures. Three types of simple boundary conditions are assumed for phonon transport at the surface; (i) full reflection, (ii) full transmission in an entire surface region, and (iii) full transmission in a limited region between gate and drain electrodes, where a local heat sink with a thermal bump is placed on the surface. Fig. 7 shows simulated temperature profiles in the channel of HEMTs with the three different boundary conditions of phonon transport at the surface. Preliminary results suggest that a heat removal structures on the surface is effective in suppressing channel-temperature increase, even if it is placed above the high-temperature region.



Figs. 4 (a) Transconductance as function of gate length (L_g) with and without local-heating effect, and (b) change in total number of particles (ΔQ_{total}) in device model for electron-transport simulation by changing applied gate-to-source voltage (Vds)

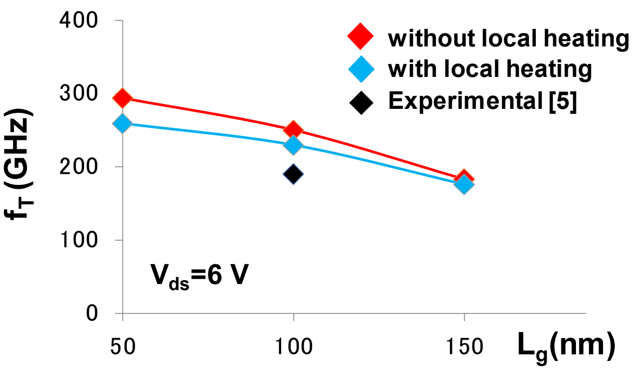


Fig. 5 Unity-current gain cut-off frequency (f_T) as a function of L_g with and without local-heating effect

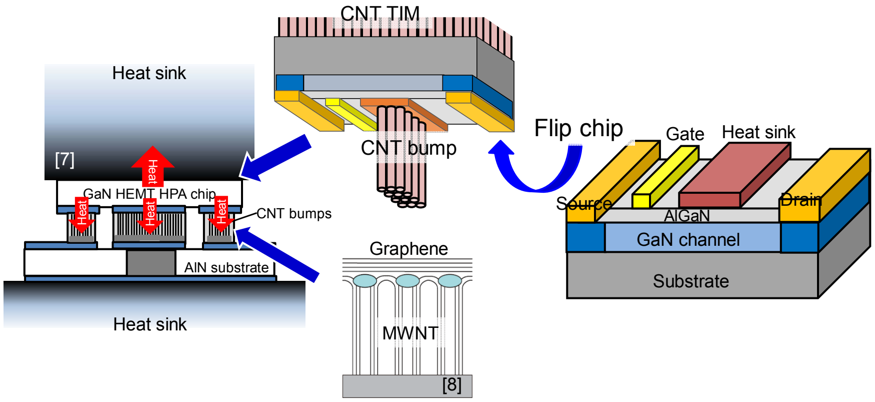


Fig. 6 Schematic image of flip-chip HEMT HPA with nano-carbon bumps and a thermal-interface material (TIM) [6-9].

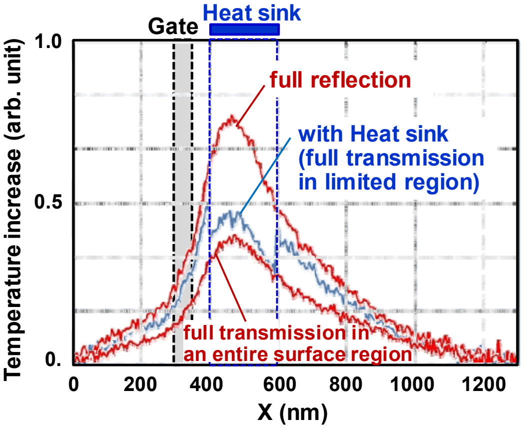


Fig. 7 Channel-temperature profiles in a 50-nm-gate-AlGaN/GaN HEMT under different conditions of phonon reflection and transmission across device surface.

IV. CONCLUSION

We applied a quasi-self-consistent electron-phonon transport Monte Carlo simulation method, in which local-phonon distribution is considered, to simulate the high-frequency characteristics of nm-gate GaN HEMTs. The simulations suggest that a shorter gate HEMT exhibits larger performance degradation in cut-off frequency due to the local-heating effect. We also simulated HEMTs with heat-removal structures on the surface, suggesting its effectiveness in suppressing channel-temperature increase.

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