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Coupled Monte Carlo-Energy Relaxation Analysis of Hot-Carrier Light Emission in MOSFET's

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We develop the new two-dimensional device simulator to analyze the hot carrier light emission for the first time. The new calculation algorithm of coupled Monte Carlo-Energy Relaxation analysis is employed to obtain the carrier temperature distribution and the carrier energy distribution at the fast computation turn-around time. We can easily obtain the relation between the hot carrier energy and the light emission characteristics by using this simulator. The excellent agreement between the simulated and experimental results is obtained. It is found from the comparison between the simulated and experimented results that the hot carrier energy distribution can not be described by Maxwell-Boltzmann distribution.

1. Introduction

As the size of MOSFET's is scaled-down, the carrier energy is significantly increased. Consequently, the device performance and reliability are more significantly influenced by carriers with high energy, that is, hot carriers. Therefore, it is very important to accurately evaluate the carrier energy distribution in the small size devices. The carrier energy distribution has been evaluated so far by measuring the light emission characteristics[1]. However, it is impossible to obtain the absolute value of carrier energy and the microscopic spatial energy distribution by the light emission measurement. Thus, it has been required to develop the device simulator which can calculate the carrier energy distribution from the hot carrier light emission characteristics. In this paper, we discribe the new two-dimensional device simulator to calculate the relation between the hot carrier light emission characteristics and the carrier energy distribution.

2. Physical Model for Light Emission

Several physical models such as the radiation recombination, the bremsstrahlung radiation and the intra-band transition of energetic holes in the valence band etc. have been proposed for the light emission in the Si devices. In our simulator, we assume the bremsstrahlung radiation model as the light emission model in n-channel MOSFET. In the bremsstrahlung radiation , the hot electrons emit the photons when the electron trajectory is sharply bent by the ionized impurity. Therefore, the hot carrier light emission is observed in the drain region near the channel because there are many hot electrons and ionized donor impurity around the drain region. Assuming that the hot carriers are scattered by a coulomb potential of the ionized impurities, the photon emission cross section due to the bremsstrahlung radiation is described as follows[2];

$$P(E,h\nu) \propto \frac{f(E,h\nu)}{E} \ln \frac{(\sqrt{E}-\sqrt{E-h\nu})^2}{E} \qquad (1)$$

where E is an initial electron energy, $h\nu$ is an emitted photon energy and $f(e,h\nu)$ is Sommerfeld factor which is a correction factor to minimize the calculation error in Born approximation.

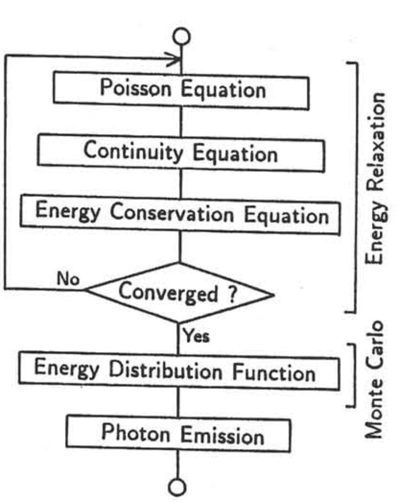

Fig. 1. Flow chart for coupled Monte Carlo - Energy Relaxation analysis.

3. Simulation Algorithm

To calculate the light emission intensity, the spatial distribution and the distribution function of electron energy or electron temperature have to be obtained. Especially, a higher energy portion of the distribution function should be calculated more accurately because a few high energy electrons fulfill an important role in the light emission. In our simulator, the potential, the carrier density and the average carrier temperature are calculated at the first according to the energy relaxation analysis with hydrodynamic model as shown in Fig.1 [3],[4]. Then, the electron energy distribution is calculated by using the obtained potential distribution along the current flow from the source to the emission point according to the one-dimensional Monte Carlo analysis in which the non-parabolic spherical band model is used [5]. Finally, the light intensity is calculated by the convolution of the electron energy distribution function and the photon emission cross section of bremsstrahlung radiation.

4. Experimental

The device used in this study is a conventional poly-Si gate n- channel MOSFET which was fabricated in our facility. The effective channel length, the channel width , and the gate oxide thickness are 1.8μm, 20μm, and 35nm, respectively. Hamamatsu hot-electron analyzer C3230-2 was employed for measuring the hot carrier light emission. The light with the wave length of 280nm to 1100nm can be directly observed through a microscope in this equipment. Several filters were used to measure the photon energy distribution of the emitted light.

5. Results and Discussion

The electron temperature distribution along the channel calculated with the coupled Monte Carlo-Energy Relaxation simulator is shown in Fig.2. It is clear in the figure that the electron temperature abruptly increases near the drain edge. The contour map of the electron temperature at Vg=3V and Vd=6.6V is shown in Fig.3 where the highest temperature at the drain edge exceeds 4700K. The corresponding contour map of light intensity is shown in Fig.4. The light emission region is strongly localized at the drain edge near the channel where the electron temperature is very high. However, the highest emission region is slightly different from the highest temperature region as is obvious when Fig.4 is compared with Fig.3. This is because the maximum electron current path does not always pass through the highest electron temperature region. Both higher electron temperature and higher electron density are necessary for emitting the light with higher intensity. Figure 5 depicts the electron energy distribution at the highest light intensity region which is calculated by Monte Carlo analysis. The average electron temperature calculated from this electron energy distribution shows the excellent agreement with that obtained by the energy relaxation analysis. Therefore, we can successfully coupled the energy relaxation analysis with Monte Carlo analysis. The simulated light intensity at the wave length of 600nm(2.07eV) and 1000nm(1.24eV) is plotted versus the gate voltage in Fig.6 where the measured results are also plotted for the comparison. The simulated and measured substrate current are also plotted in the figure. The excellent agreements are obtained between the simulated results and the measured results. As is obvious in the figure, the light intensity represents the similar gate voltage dependence to that of the substrate current and thus shows the maximum at the gate voltage which is lower than the drain voltage. This is because the electron density increases while the electron temperature decreases when the gate voltage is increased. The maximum light intensity is decreased with decreasing the wave length and hence

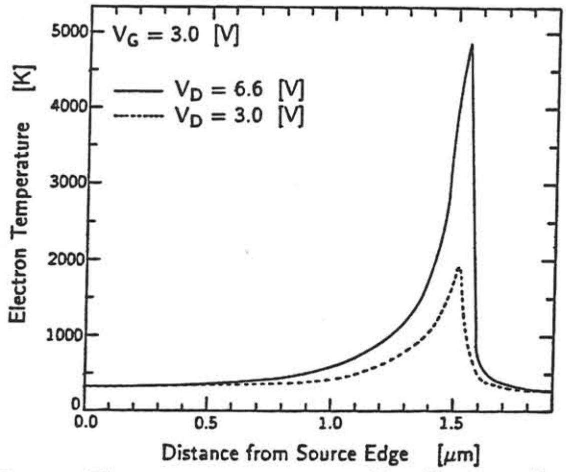

Fig. 2. Electron temperature distribution along the surface at V_G = 3 [V] changing V_D as a parameter.

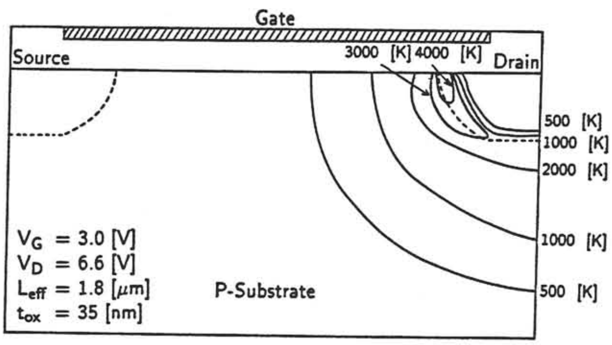

Fig. 3. Contour map of electron temperature at V_G = 3 [V], and V_D = 6.6 [V].

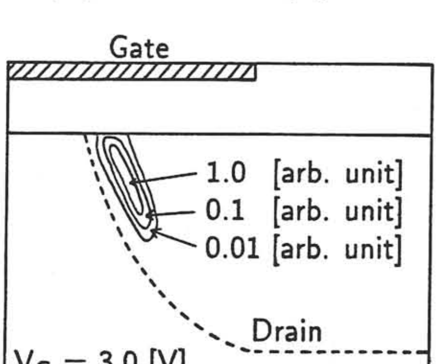

Fig. 4. Contour map of normalized light intensity at V_G = 3 [V], and V_D = 6.6 [V].

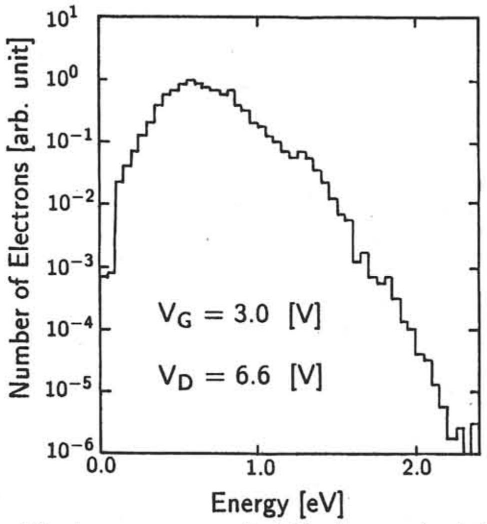

Fig. 5. Electron energy distribution calculated using Coupled Monte Carlo - Energy Relaxation analysis at $V_G = 3$ $[V]$, and $V_D = 6.6$ $[V]$.

increasing the photon energy. In addition, the gate voltage which gives the maximum light intensity is decreased with decreasing the wave length. This implies that the higher electric field and hence the higher electron temperature are required for emitting the light with higher photon energy and the number of electrons with higher energy is smaller. The simulated photon energy distribution of the emitted light is compared with the experimental result in Fig.7. The photon energy distribution calculated from Maxwell-Boltzmann distribution is also shown in the figure. A good agreement was obtained between the simulated result with the coupled Monte Carlo-Energy Relaxation analysis and the experimental results in the photon energy range of 1.5eV to 2.4eV. Meanwhile, the simulated result obtained from Maxwell-Boltzmann distribution

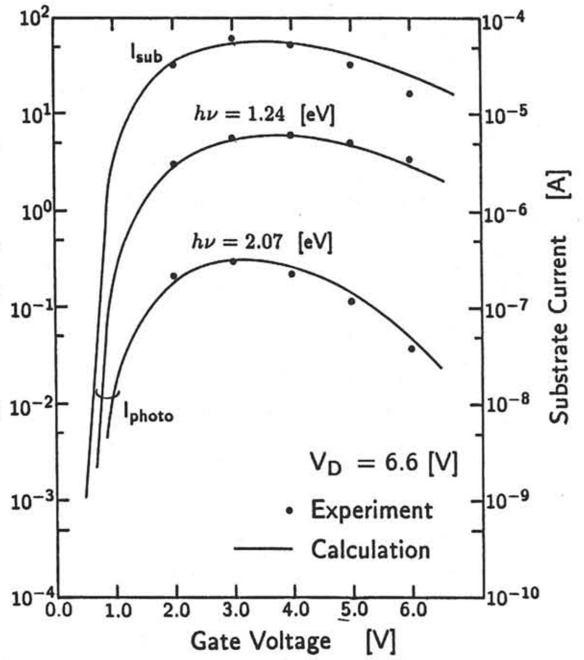

Fig. 6. Gate voltage dependence of light intensity and substrate current at $V_D = 6.6$ $[V]$.

shows a very poor agreement with the experimental results. This strongly suggest that the hot carrier energy distribution is not described by Maxwell-Boltzmann distribution.

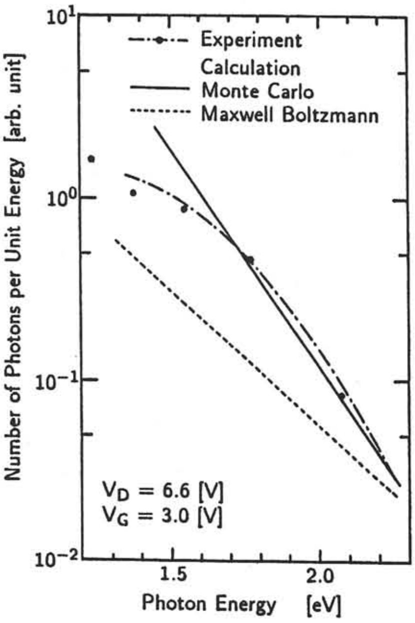

Fig. 7. Energy spectrum of photons emitted from n-channel MOSFET at $V_G = 3$ $[V]$, and $V_D = 6.6$ $[V]$.

6. Conclusion

We demonstrated the new coupled Monte Carlo-Energy Relaxation simulator to analyze the hot carrier light emission. The excellent agreements are obtained between the simulated results and experimental results. We found from the comparison between the simulated results and experimental results that the hot carrier energy distribution can not be described by Maxwell- Boltzmann distribution.

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