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Full Length Research Paper

The effect of light illumination in photoionization of deep traps in GaN MESFETs buffer layer using an ensemble Monte Carlo simulation

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Deep traps can produce serious degradation in the drain current and consequently the output power of GaN based FETs. This current collapse phenomenon represents a significant impediment to the incorporation of these devices in electronic systems. In this article trapping of hot electron behavior by deep trap centers located in buffer layer of a wurtzite phase GaN MESFET has been simulated using an ensemble Monte Carlo simulation. The simulated results show the trap centers are responsible for current collapse in GaN MESFET at low temperatures. These electrical traps degrade the performance of the device at low temperature. On the opposite, a light-induced increase in the trap-limited drain current, results from the photoionization of trapped carriers and their return to the channel under the influence of the built in electric field associated with the trapped charge distribution.

Key words: Buffer layer, current collapse, light-induced, photoionization, drain current.

INTRODUCTION

GaN has been a subject of intense investigation recently for blue and ultraviolet light emission, high-temperature, high-power electronic devices and solar blind ultraviolet detectors (Look, 2005). Also the material has a relatively high electron saturation drift velocity and low relative permittivity, implying potential for high frequency performance. However, set against the virtues of the material are disadvantages associated with material quality. GaN substrates are not readily available and the lattice mismatch of GaN to the different substrate materials commonly used means that layers typically contain between 10^8 and 10^{10} threading dislocations per square centimeter. Further, several types of electron trap occur in the device layers and have a significant effect on GaN devices.

In the search for greater power and speed performance, the consideration of different aspects that severely limits the output power of GaN FETs must be accounted for. It is found that presence of trapping centers in the GaN material is the most important phenomenon which can have effect on current collapse in output drain current of GaN MESFET. This effect was recently experimentally investigated in GaN MESFET and it was observed that the excess charge associated with the trapped electrons produces a depletion region in the conducting channel which results in severe reduction in drain current (Kim et al., 1999). The effect can be reversed by liberating trapped electrons either thermally by emission at elevated temperatures or optically by photoionization (Chattopadhyay et al., 1981). There have been several experimental studies of the effect of trapping levels on current collapse in GaN MESFET (Tsukazaki et al., 2005). For example, Bellotti et al. (1999) measured photoionization spectroscopy of traps in GaN MESFET transistors and calculated that the current collapse resulted from charge trapping in the buffer layer. Makino et al. (2001) observed that decreases in the drain current of a GaN FET correspond to the deep trap centers located at 1.8 and 2.85 eV. In this work, we report a Monte Carlo simulation which is used to model electron transport in wurtzite GaN MESFET including trapping centers effect. This model is based on the fact that since

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optical effect can emit the trapped electrons that are responsible for current collapse, the incident light wavelength dependence of this effect should reflect the influence of trap centers on hot electron transport properties in this device.

MODEL, DEVICE AND SIMULATIONS

An ensemble Monte Carlo simulation has been carried out to simulate the electron transport properties in GaN MESFET. The method simulates the motion of charge carriers through the device by following the progress of 10^4 superparticles. These particles are propagated classically between collisions according to their velocity, effective mass and the prevailing field. The selection of the propagation time, scattering mechanism and other related quantities is achieved by generating random numbers and using this numbers to select, for example, a scattering mechanism. Our self-consistent Monte Carlo simulation was performed using an analytical band structure model consisting of five non-parabolic ellipsoidal valleys. The scattering mechanisms considered in the model are acoustic, polar optical, ionized impurity, piezoelectric and nonequivalent intervalley (scatte, 1989). The nonequivalent intervalley scattering is between the Γ_1, Γ_3, U, M and K. The parameters used in the present Monte Carlo simulations for wurtzite GaN are the same as those used by Arabshahi for MESFETs transistor (Moglestue, 1993).

The device structure illustrated in Figure 1a is used in all the simulations. The overall device length is 3.3 µm in the x-direction and the device has a 0.3 µm gate length and 0.5 µm source and drain length. The source and drain have ohmic contacts and gate is in Shottky contact in 1 eV to reperesent the contact potential at the Au/Pt. The source and drain regions are doped to 5×10^{23} m^{-3} and the top and down buffer layers are doped to 2×10^{23} and 1×10^{22} m^{-3}, respectively. The effective source to gate and gate to drain separation are 0.8 and 1.2 µm, respectively. The large dimensions of the device need to a long simulation times to ensure convergence of the simulator. The device is simulated at room temperature and 420 K.

In the interests of simplicity, it is assumed that there is just a single trap with associated energy level E_T in all or just part of the device. Further, it is assumed that only electrons may be captured from the conduction band by the trap centers, which have a capture cross-section σ_n and are neutral when unoccupied, and may only be emitted from an occupied centre to the conduction band. We use the standard model of carrier trapping and emission (Ridley, 1997).For including trapping centre effects, the following assumption has been considered. The superparticles in the ensemble Monte Carlo simulation are assumed to be of two types. There are mobile particles that represent unbound electrons throughout the device. However, the particles may also undergo spontaneous capture by the trap centers distributed in the device. The other type of superparticles is trapping centers that are fixed at the centre of each mesh cell. As illustrated in Figure 1b, each trap centre has the capacity to trap a finite amount of mobile electronic charge from particles that are in its vicinity and reside in the lowest conduction band valley. The vicinity is defined as exactly the area covered by the electric field mesh cell. The finite capacity of the trapping centre in each cell of a specific region in the device is set by a density parameter in the simulation program. The simulation itself is carried out by the following sequence of events. First, the device is initialized with a specific trap which is characterized by its density as a function of position, a trap energy level and a capture cross-section. Then at a specific gate bias the source-drain voltage is applied.

Some of the mobile charges passing from the source to the drain in each timestep can be trapped by the centers with a probability which is dependent on the trap cross-section and particle velocity in the cell occupied at the relevant time *t*. The quantity of charge that is captured from a passing mobile particle is the product of this probability and the charge on it. This charge is deducted from the charge of the mobile particle and added to the fixed charge of the trap center. The emission of charge is simulated using the emission probability. Any charge emitted from a trap centre is distributed evenly to all mobile particles in the same field cell. Such capture and emission simulations are performed for the entire mesh in the device and information on the ensemble of particles is recorded in the usual way.

RESULTS AND DISCUSSION

The application of a high drain-source voltage causes hot electrons to be injected into the buffer layer where they are trapped by trap centers. The trapped electrons produce a depletion region in the channel of the GaN MESFET which tends to pinch off the device and reduce the drain current. This effect can be reversed by any factor which substantially increases the electron emission rate from the trapped centers, such as the elevated temperatures considered previously. Here we consider the effect of exposure to light (Mansouret al., 1991).

There have been several experimental investigations of the influence of light on the device characteristics. Di et al. (1991) were the first to study experimentally the current collapse in GaN MESFETs as a function of temperature and illumination. They showed that the photoionization of trapped electrons in the high-resistivity GaN layers and the subsequent return of these electrons to the conduction band could reverse the drain current collapse. Their measurements were carried out as a function of incident light wavelength with values in the range 380 to 720 nm, corresponding to photon energies up to 3.25 eV which is close to the GaN band gap. Their results show that when the photon energy exceeds the trap energy, the electrons are quickly emitted and a normal set of drain characteristics are observed. To examine the photoionization effect in our simulations, the thermal emission rate e^t_n was changed to $e^t_n+e^o_n$, where $e^o_n \sim\sigma^o_n \Phi$ is the optical emission rate, with σ^o_n, the optical capture cross-section and Φ the photon flux density given by

$$\Phi=\frac{I}{h\nu}=\frac{I\lambda}{hc} \tag{1}$$

where I is the light intensity, ν is the radiation frequency and λ is the incident light wavelength.

Our modelling of photoionization effects in GaN MESFETs is based on parameters used by Binari and Chen (Chen et al., 1998). The simulations were all carried out for two different deep trap centers, both with a concentration of 10^{22} m^{-3}, and with photoionization threshold energies at 1.8 and 2.85 eV and capture cross-sections of 6×10^{-21} and 2.8×10^{-19} m^2, respectively. A fixed

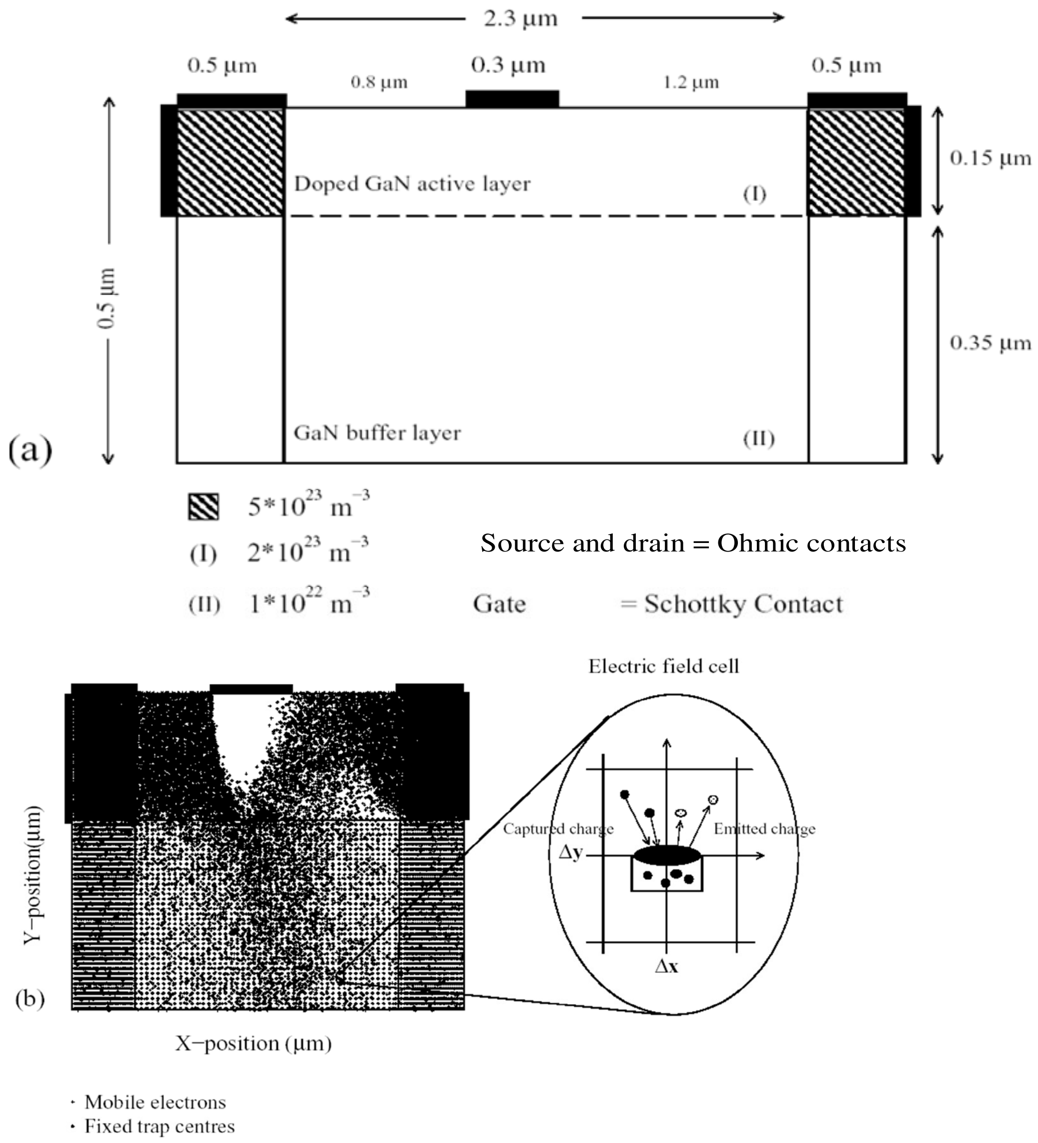

Figure 1. (a) Cross section of wurtzite GaN MESFET structure which we have chosen in our simulation. Source and drain contacts have low resistance Ohmic contacts, while the gate contact forms a Schottky barrier between the metal and the semiconductor epilayer, (b) The instantaneous distribution of 10^4 particles at steady forward bias (drain voltage 50 V, gate voltage -1 V), superimposed on the mesh. Note that in the simulation there are two types superparticles. The mobile particles which describe unbound electron flow through the device and trapping centre particles which are fixed at the centre of each electric field cell (in this case in the buffer layer only). The ellipse represents a trap center which is fixed at the centre of an electric field cell and occupied by some mobile charges.

incident light intensity of 5 Wm^{-2} at photon energies of 2.07 and 3.1 eV is used. The simulations have been performed at a sufficiently high temperature (450 K) for both thermal and optical emission to be significant as well as at room temperature.

Figure 2a illustrates the effect on the drain current characteristics of exposure of the device to light at room temperature. The GaN MESFET has a deep trap centre at 1.8 eV and is illuminated at photon energy of 2.07 eV. It can be seen that in the light the *I-V* curves generally exhibit a larger drain current, especially at higher drain voltages, reflecting the fact that the density of trapped electrons is much lower. Simulations have also been performed at 420 K for a device with deep level traps at 2.85 eV. The simulation results in Figure 2b for illumination of a photon energy of 3.1 eV are compared with the collapsed *I-V* curves in the absence of light. Comparison of Figures 2a and b shows that the currents

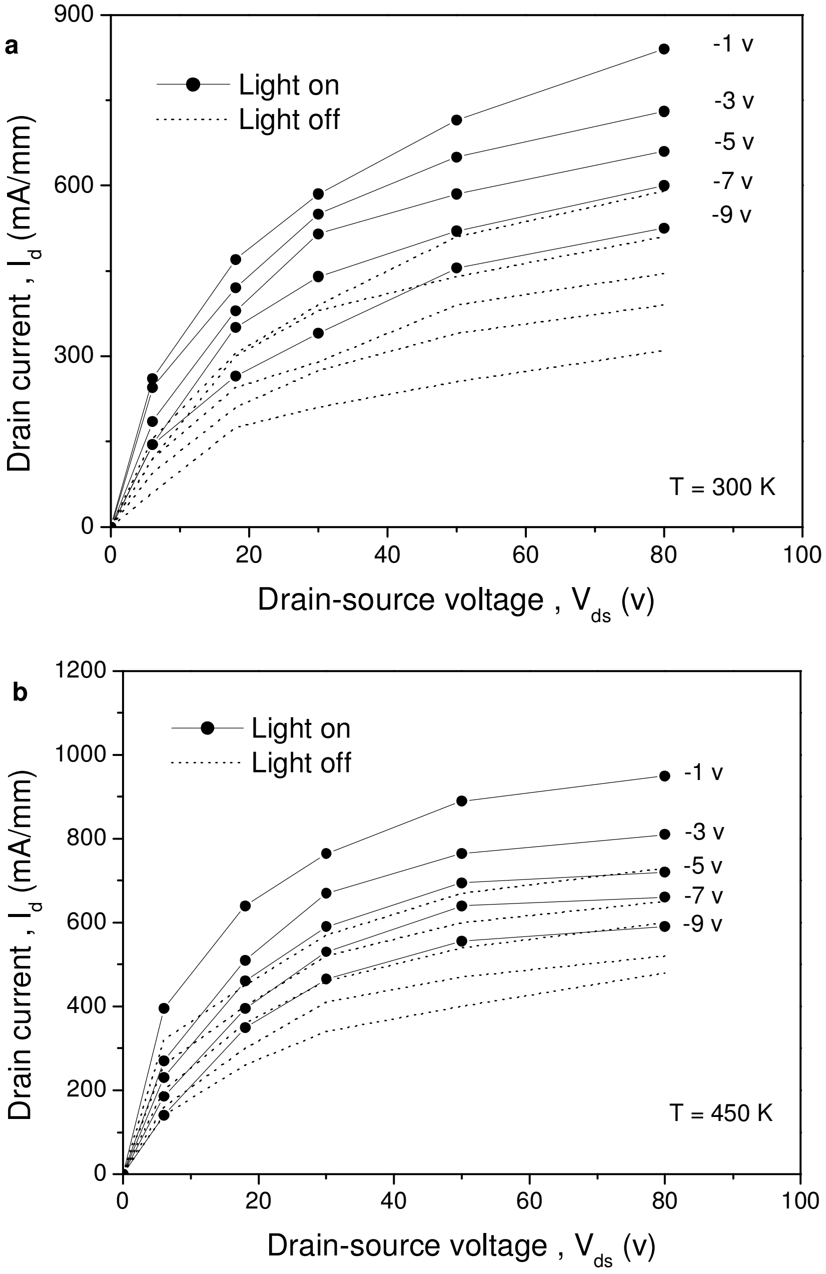

Figure 2. *I-V* characteristics of a GaN MESFET under optical and thermal emission of trapped electrons (solid curve) and thermal emission of trapped electrons (dashed curve) at two different temperatures. (a) T=300 K with trap centers at 1.8 eV and illuminated with a photon energy of 2.07 eV. (b) T=450 K with trap centers at 2.85 eV and illuminated with a photon energy of 3.1 eV.

are generally higher at 420 K and that the light has less effect at higher temperature.

Having described the macroscopic characteristics derived from the simulations, Figures 3 to 5 demonstrate some microscopic details that can also be extracted. Figures 3a and b show a contour plot of the conduction band edge without trap centers and with trap centers effects, respectively. The source is located on the left and the drain is on the right. Because of the source has a higher potential energy than the drain, electrons lose potential and gain kinetic energy as they move from source to drain. It should be noted that much of the drain

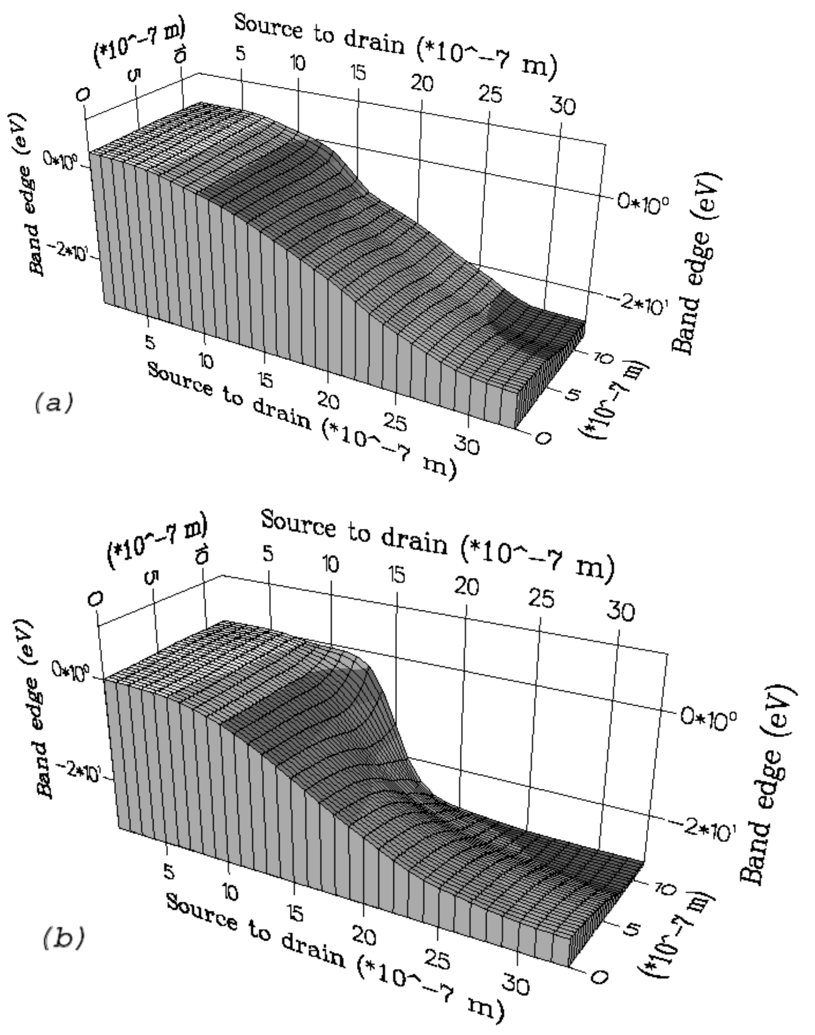

Figure 3. Steady-state Γ valley band profile through the simulated GaN MESFET for (a) free trapped centers and (b) including trapping effect at room temperature when V_{ds}=30 V, and the gate bias is -1 V.

source bias is dropped in the vicinity of the gate region. Near the drain, the conduction band is quasi-flat which incorporates high supply doping and hence a large sheet electron density. Another dominant feature of Figure 3a is the potential drop at the drain edge of the gate. This potential drop generates hot electrons which can diffuse into the GaN buffer layer where they can be trapped. As a comparison Figure 3b shows results including trapping centers effects. It is seen that the presence of trap centers increases the sharp potential drop seen in Figure 3a and also strongly affects the potential between source and gate. This affects electron confinement, which is the main reason for a lower output drain current.

Figure 4 shows the total electron density for the simulated device, when the drain-source potential drop is 30 V, and the gate bias is -1 V. Figure 5 shows the longitudinal electron drift velocity throughout the device. As it can be seen, the drift velocity reaches to $2\times10^5\,ms^{-1}$ under the gate, as a result of the quasi-ballistic acceleration caused by the steep potential variation. Near the drain, the velocity exhibits a sharp reduction due to electron transfer into the higher satellite valleys.

Conclusions

The effect of light illumination in photoionization of deep traps in GaN MESFETs buffer layer was simulated in a GaN MESFET for a single tapping center. Traps in the simulated device produce a serious reduction in the drain current and consequently the output power of GaN MESFET. The drain current behavior as a function of illumination with photon energy was also studied. Our results show that as the temperature and photon energy

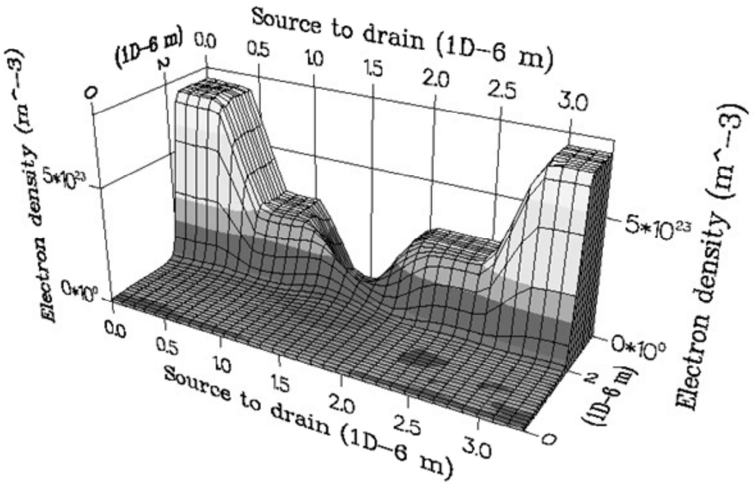

Figure 4. Electron density throughout the modeled region of GaN MESFET including trapping effect, when V_{ds}=30 V, and the gate bias is -1 V. Note partial depletion of charge under the gate and in the vicinity of source and drain.

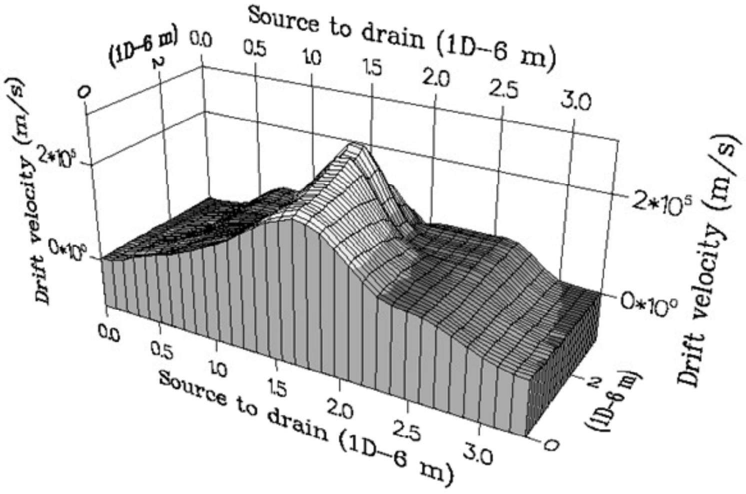

Figure 5. Steady-state longitudinal electron drift velocity in the simulated GaN MESFET including trapping effect, when V_{ds}= 30 V, and the gate bias is -1 V. Note in the high field regions under the gate electrons are accelerated, gaining sufficient velocity to enter to the upper conduction valleys.

are increased, the collapsed drain current curve moved up toward the non-collapsed curve due to more emission of trapped electrons.

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