Extended Abstracts of the 1999 International Conference on Solid State Devices and Materials, Tokyo, 1999, pp. 214-215

The Potential of III-Nitrides for Use in High-Speed Field-Effect Transistors

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1. Introduction

Over the past few years, there has been a rapid progress both in the physical understanding and in the technology of III-Nitrides (AlN, GaN and InN). These materials are suitable for a broad range of optoelectronic applications and for high power, high frequency amplifiers. For the latter, a large band gap and high electron velocities combined with high low field mobilities are important. GaN as well as InN show these properties. Recently Monte Carlo simulations of the stationary electron transport in both wurtzite and zincblende GaN [1] and InN [2] have been published. A Monte Carlo study of the nonstationary electron transport in both GaN lattice types has been carried out [3]. It revealed that the electron transit times over distances in the range from 0.2 µm to 1 µm in GaN are comparable or even shorter than in GaAs.

Experimental AlGaN/GaN MODFET with promising RF properties have been reported recently. Worth metioning are a transistor (gate length 0.25 µm) with a cut off frequency of 53 GHz [4], a 0.12 µm gate transistor showing a maximum frequency of oscillation of 103 GHz [5] and a AlGaN/GaN MODFET on SiC substrate with a record output power density of 6.8 W/mm at 10 GHz [6].

Until now, there are no publications dealing with the potential of InN for high frequency field effect transistors. The aim of this work is to define a figure of merit which can be used to compare the electron transport properties of different semiconductors and to estimate their potential for use in high-speed FETs. This FOM is used to compare the electron transport in GaAs, wurtzite and zincblende GaN, and InN.

2. Definition of the Figure of Merit $f_{T\max}$

To compare the electron transport properties of different semiconductors we introduce the FOM $f_{T\max}$, which can be calculated in the following way. We assume that a field step is applied to a homogenous semiconductor sample at time t=0. By means of the relaxation time approximation (RTA, details can be found in [7]) one can easily calculate the time τ an electron needs to cross a distance x. For every distance, which can be interpreted as the gate length of an FET, $f_{T\max}$ can be obtained by

$$f_{T\max} = \frac{1}{2 \times \pi \times \tau_{\min}}$$

where $\tau_{\min}$ is the minimum transit time for the case of optimum field conditions. It should be noted that $f_{T\max}$ is different from, but related to, the cut off frequency f_T of FETs. $f_{T\max}$ can be interpreted as an uppermost limit for transistor speed. In real transistors f_T will always be lower than $f_{T\max}$ because here the field conditions differ from the optimum conditions we used for the calculation of $f_{T\max}$, and because transistor speed is not only determined by the electron transit time, but also by several parasitic effects in the transistor such as fringing capacitances, parasitic resistances and possibly short channel effects. Nevertheless, a high $f_{T\max}$ is mandatory for the semiconductors used for high-speed transistors.

The input parameters for accurate RTA calculations are the stationary dependences

- electron velocity - electric field (v-E),
- electron energy - electric field (w-E), and
- electron effective mass - electric field (m*-E),

which can be obtained by Monte Carlo simulations. Because in many cases only v-E and w-E are published in the literature, e.g. in the case of InN [2], we carried out extensive test calculations for GaAs and Si (for these materials the three dependendences are given e.g. in [7], [8]) and found, that for the aim of this study (distances in the range of 0.1 to 1 µm) it is possible to calculate accurate values for the electron transit time, even if only the first two relationships are known. In this case, for m* the constant value for the minimum of the main valley (which is known for almost all semiconductors), or an energy dependent m* taking into account only the nonparabolicity of the main valley, has to be used.

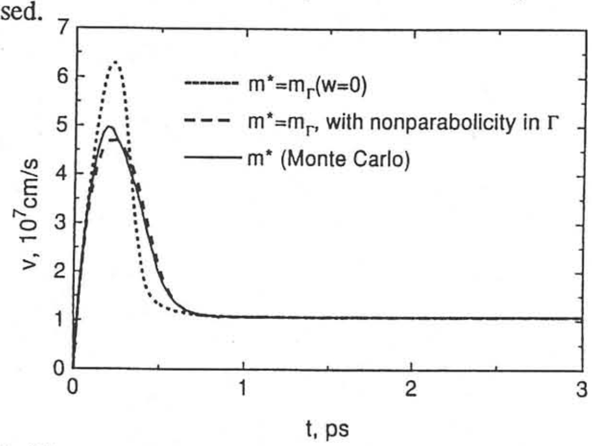

Fig. 1 Electron velocity vs. time in GaAs after applying a field step from E=0 to E=20 kV/cm.

Figure 1 shows the simulated electron velocity vs. time in GaAs. The field step applied is 20 kV/cm. In the case of a constant effective mass a strong but short velocity overshoot is obtained. In the cases of an energy dependent mass in the Γ valley and of the accurate effective mass (result of Monte Carlo simulations, [7]) the electron velocities differ only slightly showing a lower peak value but a longer velocity overshoot compared to the first case. The electron transit time for a distance of 0.5 µm is nearly the same in all three cases (the difference is less than 1%).

These results show that the effective mass in the main valley (in the case of GaAs the Γ valley) has the greatest effect on velocity overshoot if the relative energy gap between the valleys is in the order of 0.3 eV (as in the case of GaAs) or greater (as e.g. in the case of InN). A similar observation has been made in [3].

3. Results

For the four semiconductors GaAs (the classical material for high-speed FETs), wurtzite and zincblende GaN, and InN, the electron transport has been simulated for a variety of field conditions and distances. For GaAs the accurate v-E, w-E, and m*-E Monte Carlo characteristics from [7] have been used. In the case of both GaN phases we took the v-E and w-E dependences from [1] and calculated the m*-E characteristics using the field dependent valley occupations [1] and the nonparabolicity factors as well as the effective masses (at the valley minima) from [3] and [9]. Because there are no data for the field dependent effective mass in InN, we used the Monte Carlo v-E and w-E characteristics from [2] and an energy dependence of m* described only by the nonparabolicity of the main valley.

As an example of the simulated electron transport, Fig. 2 shows the electron velocity in GaAs (field step 20 kV/cm) and in both GaN phases (field step 450 kV/cm). Strong velocity overshoot occurs in all three materials, but in the case of GaN much higher fields (or voltages) are necessary to produce a noticeable overshoot. A second difference is the distance over which overshoot can be observed. This distance is much shorter in GaN.

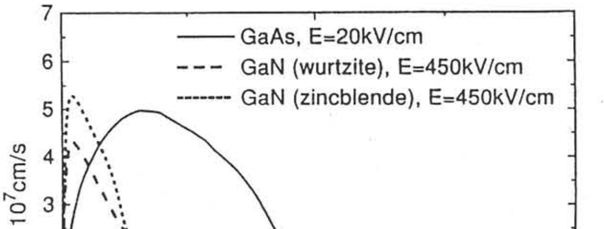

Fig.2 Simulated electron velocity vs. distance in GaAs and GaN.

Fig. 3 is the core of our work. Here, the FOM f_{Tmax} is shown as a function of distance (or gate length). The calculated f_{Tmax} values for zincblende and wurtzite GaN are almost the same with slightly higher values for the zincblende material. For distances above 0.4 µm the FOM for GaAs is lower than for GaN. This agrees with the results from [3]. More important is the fact that InN shows the highest f_{Tmax} over the whole distance range of our investigation. At distances of 0.1, 0.5, and 1 µm, the obtained values for f_{Tmax} are 736 GHz, 135 GHz, and 67 GHz, respectively. For comparison, in GaAs these values are 677 GHz, 76 GHz, ad 32 GHz. This is an clear indication that InN could be an excellent material for high-speed transistors.

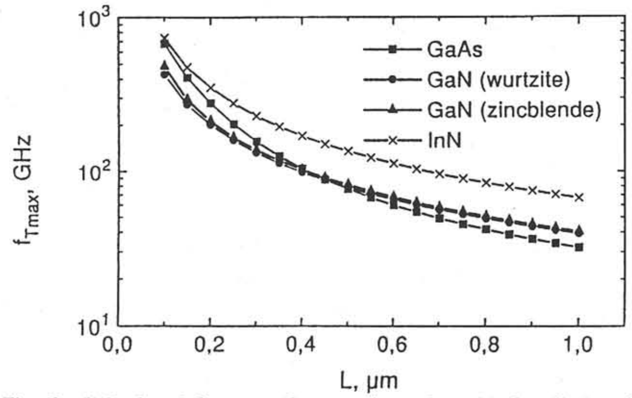

Fig. 3 Calculated f_{Tmax} vs. distance (gate length) for GaAs, GaN (wurtzite and zincblende) and InN.

5. Conclusion

By means of the calculation of the defined FOM f_{Tmax} the potential of GaN and InN for use in high-speed transistors has been investigated. It is shown, that f_{Tmax} for both GaN phases is comparable to that of GaAs except for extremely short distances (gate lengths). InN shows an f_{Tmax} higher than that of the other three materials investigated. We conclude that InN is a promising material for high-speed FETs. The extremely high f_{Tmax} combined with an bandgap of 1.9 eV, which is about 0.5 eV larger than that of GaAs, InN FETs could operate at very high frequencies **and** deliver very high output powers. This ability could extend the application of semiconductors in the field of high power high frequency amplification.

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