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Potential of wide bandgap semiconductor devices for high-temperature applications

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ABSTRACT: We evaluate and compare temperature dependencies of a low field electron mobility in β-SiC, α-SiC, and GaN for different carrier concentrations and compensation levels and simulate the high field transport properties of these semiconductors using the Monte Carlo technique. We also review existing and our own experimental data for both SiC and GaN contacts and analyze the potential performance of wide band gap FETs at temperatures up to 700 °C.

1. INTRODUCTION

In this paper, we consider the potential of SiC, SiC/AlN, and GaN/AlN material systems for high temperature electronic applications. Our analysis is based on the theory of the electron transport, measured high temperature characteristics of ohmic and Schottky contacts, and Field Effect Transistor models which allow us to predict the device behavior at elevated temperatures.

For wide band gap semiconductors, the standard analytical theory of polar optical scattering (one of the mechanisms controlling low field mobility in these compounds) has to be revised. In all these materials, polar optical phonons have much higher frequencies than those typical for Si, Ge, or GaAs. As a consequence, the low temperature limit for polar optical scattering applies even at room temperature. Hence, an effective relaxation time can be introduced for two successive processes of the polar optical phonon absorption and emission. Large donor energies typical for wide band gap semiconductors also cause a noticeable deviation from the standard theory and lead to a different mobility dependence on the compensation level. Based on our new theory, we evaluate and compare temperature dependencies of a low field electron mobility in β-SiC, α-SiC, and GaN for different carrier concentrations and compensation levels. Our calculation shows that, at high temperatures, β-SiC may be expected to have a substantially higher mobility than α-SiC even though the difference is shrinking with an increase in temperature. These results are in qualitative agreement with experimental data. We also simulate the high field transport properties of wide band gap semiconductors using the Monte Carlo technique. In low electric fields, the Monte Carlo simulations are in good agreement with our analytical theory. In high electric fields, the transport properties are less sensitive to temperature variations.

In addition to intrinsic material properties, the temperature dependencies and stability of ohmic and Schottky contacts determine the device behavior at elevated temperatures. We review experimental data for both SiC and GaN and conclude that refractory tungsten ohmic contacts can operate up 650 °C and Schottky contacts can operate up to 700 °C. Based on these results, we analyze the performance of wide band gap field effect transistors at temperatures up to 650 °C.

2. LOW FIELD MOBILITY IN WIDE BAND GAP SEMICONDUCTORS AT ELEVATED TEMPERATURES.

Most scattering mechanisms in semiconductors in low electric fields can be described using a momentum relaxation time approximation, τ_p, applicable when a phonon energy is much smaller than the average electron energy. In wide-gap semiconductors, such as GaN, the optical phonon energy, $\hbar\omega_o$, is much greater than the thermal temperature, even at room temperature. In a non-degenerate GaN, the optical polar phonon energy is about 0.1 eV. Gelmont et al (1993) showed that τ_p can be still introduced when $\hbar\omega_o >> k_BT$. Based on this approximation, they developed the analytical theory for the low field mobility in wide band gap semiconductors. Some of the results are shown in Fig. 1 - 5.

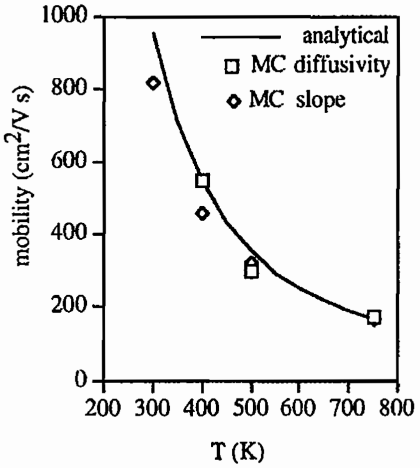

Fig. 1. Mobility temperature dependence for electrons in GaN doped at 10^{17} cm^{-3}. Solid line - analytical calculation, diamonds are from the velocity slope extrapolated to zero field (Monte Carlo simulation), squares are from the diffusion coefficient and the Einstein relation (Monte Carlo simulation).

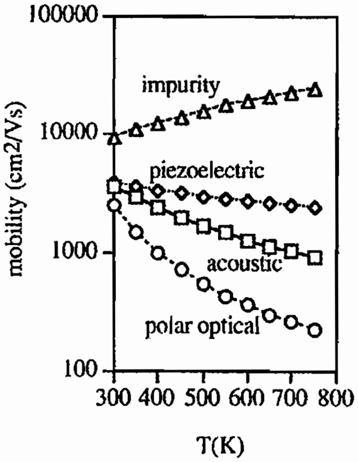

Fig. 2. Electron mobility in GaN limited by different scattering processes.

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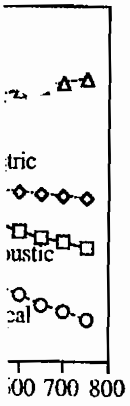

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In the temperature range between 300 K and 700 K, the electron mobility temperature dependence in GaN can be interpolated by

$$\mu\left(cm^2/Vs\right)=2100-1690\left(\frac{T}{300}\right)+375\left(\frac{T}{300}\right)^2.$$

The dominant scattering mechanism in GaN is polar optical phonon scattering (see Fig. 2). In pure undoped samples, the impurity scattering is less important. However, in highly compensated samples it may become even more important than polar optical phonon scattering even at elevated temperatures. In SiC samples, the acoustic scattering is dominant at elevated temperatures (see Fig. 3). The electron mobility in GaN at elevated temperatures is higher than in 3C-SiC and much higher than in 6H-SiC (see Fig. 4). The results of the calculation are in reasonable agreement with experimental data (see Fig. 5).

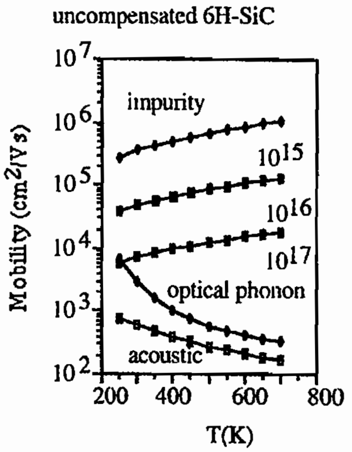

Fig. 3. Electron mobility in 6H-SiC limited by different scattering processes.

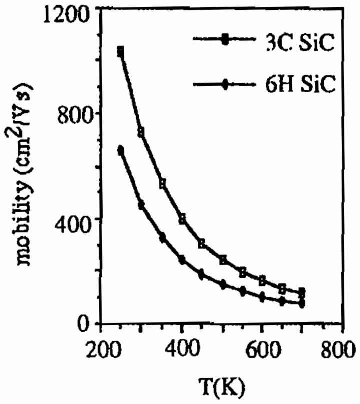

Fig. 4. Calculated temperature dependence of electron mobility for SiC.

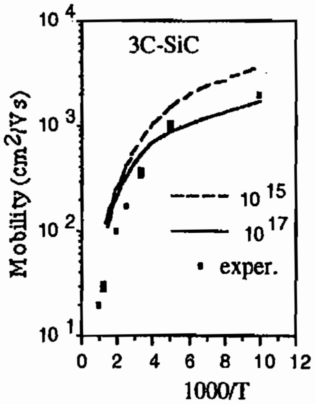

Fig. 5. Comparison with experimental data from Tashibana et al (1990). (Doping levels are in cm^{-3}.)

3. TRANSPORT PROPERTIES OF GaN AT ELEVATED TEMPERATURES.

Our ensemble Monte Carlo simulation takes into account polar optical phonon, piezoelectric, deformation potential, and ionized impurity scattering mechanisms in a non-parabolic band. Material parameters used in the simulation are the same as used by Gelmont et al (1993). The simulation results are shown in Fig. 6. As can be seen from the figure, the most important changes in the velocity-field characteristics of GaN with temperature are the decrease in the electron mobility (already discussed in Section 2), the decrease in the peak velocity, and the increase in the peak field.

The electron velocity in very high electric fields (200 to 300 kV/cm) remains practically unchanged. The peak field in GaN is very high (on the order of 100 kV/cm compared to approximately 3.5 kV/cm) in GaAs. The reason for such a shape of the velocity-field characteristic is a large intervalley separation and a very large energy of polar optical phonons in GaN (nearly three times higher than in GaAs). All in all, the GaN electron velocity at elevated temperatures is large enough for achieving high transconductance in GaN FETs, especially in short channel devices (since very high electric fields are required for velocity saturation in this material.)

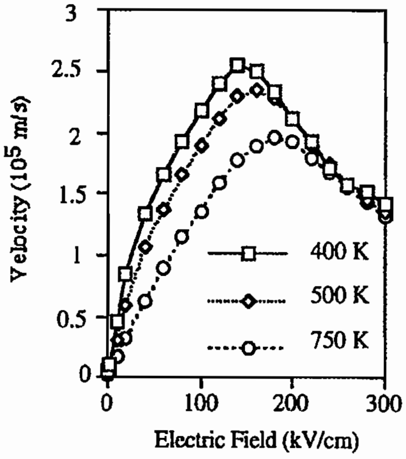

Fig. 6. Electron drift velocity in GaN doped at 10^{17} cm^{-3}.

4. OHMIC AND SCHOTTKY CONTACTS TO WIDE BAND GAP SEMICONDUCTORS AT ELEVATED TEMPERATURES.

Tables 1 and 2 list some of the measured contact resistances for ohmic contacts and barrier heights and ideality factors for Schottky contacts operating at elevated temperatures. As can be seen from Table 1, ohmic contacts to *n*-type SiC operate up to 650 °C, ohmic contacts to *p*-type SiC operate up to 450 °C, and Schottky contacts operate up to at least 700 °C. Hence, SiC FET (as opposed to bipolar devices) seem to have a better potential for operating at very high temperatures. We do not yet have similar data for GaN but we believe that ohmic contacts to this material will operate up to similar or even higher temperatures.

Material	Type	Metal	*n* or *p* (cm^{-3})	r_c (Ωcm^2)	T_{max} (°C)	Reference
3C-SiC	*n*	Ti/TiN/Pt/Au	10^{16}- 10^{17}	$1\text{x}2\text{x}10^{-4}$	650	Shor et al
3C-SiC	*n*	W/Pt/Au	10^{16}-10^{17}	$1.5 \text{ x } 10^{-4}$	650	Shor et al
6H-SiC	*n*	TiN	$1.6\text{x}10^{18}$	$4\text{x}10^{-2}$	550	Glass et al
6H-SiC	*p*	3C-SiC/Al/Ti	$1\text{-}3\text{x}10^{18}$	$2\text{x}10^{-5}$	< 450	Kelner et al
6H-SiC	*p*	Al/Ti	$2\text{x}10^{19}$	$1.5\text{x}10^{-5}$	< 450	Crafton et al

Table 1. High temperature ohmic contacts to SiC.

Material	Type	Metal	Barrier height (eV)	Ideality factor	T_{max} (°C)	Reference
3C-SiC	*n*	Pt/PtSi$_x$	0.95-1.35	2.5 - 3.5	800*	Papanicolaou et al
6H-SiC	*n*	Ti	0.85	1.04	700	Porter et al
6H-SiC	*n*	Pt	1.06	1.04	750*	Porter et al
6H-SiC	*n*	Ti	1.14	1.07	700	Porter et al

*Operated only for a short time (about 20 minutes or so). Contact stability for high temperature operation has to be investigated further.

Table 2. High temperature Schottky contacts to SiC.

5. POTENTIAL PERFORMANCE OF WIDE BAND GAP SEMICONDUCTOR FETs AT ELEVATED TEMPERATURES.

Fig. 7 shows the computed temperature dependencies of AlN/GaN HFETs with different gate lengths based on the temperature dependence of the electron mobility determined above. The calculation was done using a standard HFET model (see, for example, Shur (1990)). Parameters used in the calculation are: gate-channel separation 350 Å, saturation velocity 1.5×10^5 m/s, threshold voltage 0 V, series source and drain resistances 0.75 Ωmm.

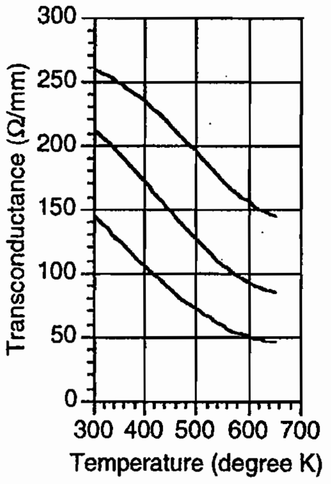

Fig. 7. Calculated transconductance of AlN/GaN FET versus temperature for gate lengths 0.5 μm (top curve), 1 μm, and 2 μm (bottom curve). Gate bias 2 V, drain bias 5 V.

As can be seen from the figure, these devices have a potential of reaching approximately the same performance at elevated temperatures as GaAs MESFETs at room temperature. Shorter channel devices should exhibit better performance since they suffer less from the mobility decrease at high temperatures. Further improvement may be reached by using thinner AlN layers.

Another advantage of AlN/GaN HFETs is a large conduction band discontinuity which may result in a smaller gate leakage current.

6. CONCLUSION.

High optical phonon energies in wide band gap semiconductors, such as SiC and GaN, lead to a relatively modest decrease of the electron mobility with temperature. Since ohmic and Schottky contacts for these materials are capable of operating at very high temperatures, both SiC and GaN are quite promising for applications in high temperature field effect transistors. In particular, the performance of AlN/GaN HFET at elevated temperatures up to 600 °C may be comparable to room temperature performance of typical GaAs MESFETs.

7. ACKNOWLEDGMENT.

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