Breakdown characteristics of MOVPE grown Si-doped GaAs Schottky diodes

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Abstract

The breakdown characteristics of Au/n-GaAs Schottky contacts on metal-organic vapor-phase epitaxy grown Si-doped n-GaAs were measured in the doping range of 6×10^{15}–1.5×10^{18} cm^{-3}. These results are compared with the experimentally measured breakdown voltages by several workers and also with the theoretical calculation predicted by Sze and Gibbons [Sze SM, Gibbons G. *Appl. Phys. Lett.* 1966;8:111]. Good agreement was observed between the measured data and the breakdown voltages by Sze and Gibbons in the high doping concentrations. The maximum depletion layer width is found to be in good agreement with the theoretical analysis by Sze and Gibbons. The breakdown voltage at higher doping concentration will be useful for the design and development of GaAs switching devices and the emitter-base region of bipolar transistors. © 1999 Elsevier Science Ltd. All rights reserved.

1. Introduction

The power rectifiers made of Schottky diodes with high-speed switching capabilities are required for a variety of power electronic applications, such as inverters, choppers, and switching power supplies [1–3]. The most useful applications of Schottky diodes are in low-voltage, high-power as well as high-speed switching power supplies and control circuits [4–7]. The limitations of the improvement of Si Schottky diode parameters are imposed by the material properties, i.e. low carrier mobility and a relative narrow band gap. Compound semiconductor materials are known to result in surface Fermi-level pinning characteristics because of high density of surface states [8]. In addition, these materials provide improved electronic transport due to higher mobilities, wider band gap and higher peak electrical field strength at breakdown. The only material mature enough technologically and superior to Si is GaAs [1]. Epitaxial structures of GaAs with low-doped and thick enough epi-layers to obtain a reasonably high breakdown voltage are available, and different types of metal for the formation of Schottky barrier (SB) diodes deposition have been developed by several authors [1,3,9–13].

The avalanche breakdown voltage of GaAs Schottky diodes are available in the literature particularly at the doping level below 5×10^{17} cm^{-3} by several authors [11–15]. However, very few results are available [16] on the breakdown voltage of GaAs diodes at doping concentration greater than 5×10^{17} cm^{-3}. The breakdown voltage at higher dopant concentration is very important to design the switching transistors and also the emitter-base region of bipolar transistors.

In this paper, we present the breakdown characteristics of Si-doped n-type GaAs Schottky diodes grown

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Table 1
Carrier concentration, thickness, breakdown voltage, maximum depletion layer width, and maximum electric field of the present investigated films

N_D (cm^{-3})	This work			
	Thickness of film (μm)	V_{BD} (V)	W_m (μm)	E_m (×10^5 V cm^{-1})
6×10^{15}	4.5	28	2.56958	2.18
2.5×10^{16}	4.5	9.982	0.75162	2.66
3×10^{16}	2	12.2	0.75854	3.22
6.88×10^{16}	4.5	4.6	0.30757	3.00
8.5×10^{16}	1	23.2	0.62143	7.47
9×10^{16}	1	11.23	0.42017	5.34
1×10^{17}	2	5.12	0.26915	3.80
1.3×10^{17}	1	8.1	0.29691	5.46
1.48×10^{17}	1	7.2	0.26236	5.49
1.5×10^{17}	2	8.2	0.27811	5.90
2×10^{17}	1	2.67	0.13744	3.90
2.45×10^{17}	1	2.5	0.12016	4.16
2.5×10^{17}	1	2.3	0.1149	4.03
3×10^{17}	2	3.5	0.12848	5.45
3.64×10^{17}	1	5.0	0.13941	7.17
6.65×10^{17}	1	2.4	0.07146	6.72
1.5×10^{18}	1	2.8	0.05139	10.90

by metal-organic vapor-phase epitaxy (MOVPE) in the concentration range of 6×10^{15}–1.5×10^{18} cm^{-3}. The maximum electric field at breakdown was then derived from the breakdown voltage at different concentration and the maximum depletion layer width. These results are compared with the other workers for comparison.

2. Estimation of breakdown voltage (V_{BD})

The breakdown voltage for the case when the low-doped base thickness t is greater than the depletion region width W is given by [17]

$$V_{BD} = \frac{\varepsilon_o \varepsilon_s E_m^2}{2qN_D},$$ (1)

where q is the electronic charge, ε_o is the permittivity of free space, ε_s is the permittivity of semiconductor. N_D is the background donor concentration, and E_m is the maximum electric field strength at breakdown at the specified background doping concentration.

If the base region is narrower than the depletion layer width, i.e. $t < W$ (a 'reach-through' diode [18]), the breakdown voltage is lowered because the depletion region reaches the highly doped contact layer. For such a reach-through (also called punch-through) case, the maximum electric field at which avalanche breakdown occurs is given by

$$E_m = \frac{V_{BD}}{t} + \frac{qN_D t}{2\varepsilon_o \varepsilon_s}.$$ (2)

The maximum depletion layer width at breakdown and the avalanche breakdown voltage can then be obtained from E_m

$$W_m = \frac{\varepsilon_o \varepsilon_s}{qN_D} E_m$$ (3)

and

$$V_{BD} = \tfrac{1}{2} E_m W_m$$ (4)

for abrupt junctions. The dependence of avalanche breakdown voltage V_{BD} for an abrupt junction on the drift region doping density N_B and energy gap E_g for Ge, Si, GaAs and GaP can be obtained from the well known Sze and Gibbons expression [19]

$$V_{BD} = 60 \left(\frac{E_g}{1.1} \right)^{3/2} \times \left(\frac{N_B}{10^{16}} \right)^{(-3/4)}.$$ (5)

Using the expression, it is possible to determine the doping level of the drift region for each semiconductor to achieve any desired breakdown voltage.

3. Experimental procedure

The Schottky diodes were fabricated on epitaxial Si-doped n-type GaAs films grown on Si-doped

($\sim 2 \times 10^{18}$ cm^{-3}) n^{+}-GaAs substrates (100) 2° off towards [110] direction using the MOVPE technique and by thermal evaporating Au under vacuum. The epitaxial n-type GaAs layers of carrier concentration 6×10^{15}–1.5×10^{18} cm^{-3} were used for this study. The details of the growth procedure can be found elsewhere [20–23]. The carrier concentrations were determined using the reverse bias capacitance–voltage (C–V) characteristics at 1 MHz on a HP 4194A LCR bridge. The carrier concentrations were further confirmed by Bio-Rad electrochemical capacitance–voltage (ECV) polaron profiler. Room temperature current–voltage (I–V) characteristics of the diodes were checked using automated arrangement consisting of a Keithley source measure unit SMU 236, an IBM PC 486, and a probe station. The breakdown voltage V_{BD} was measured at a reverse current density of 0.08 A cm^{-2}.

4. Results and discussion

The results of the measurements are summarized in Table 1. Table 1 lists the measured carrier concentration and thickness of the epitaxial layer, measured breakdown voltage, the maximum electric field and the depletion layer width at breakdown voltage. In order to compare the experimental results with the theoretical analyses, the above parameters have been plotted as a function of the donor concentration in Fig. 1. From Fig. 1 it is seen that the breakdown voltage at low carrier concentration was far from the theoretical curves obtained by Sze and Gibbons [19]. Despite some scatter in the experimental data points arising from the low doping level material, reasonably good agreement was observed with the experimental data presented by Baliga et al. [13] using the vapor and liquid phase epitaxially grown materials. However, the breakdown voltages measured by Horvath et al. [11] either in planar or mesa diodes were far below from the theoretical curves. They pointed out that this may be due to very large defect densities greater than 1×10^{6} cm^{-2} or may be due to the surface/interface effects or the edge effect influences the breakdown at low concentrations [17,24]. In the low carrier concentration (reach-through or punch-through case) the avalanche V_{BD} voltage is far from the theoretical predictions because the theoretical curves were calculated for the infinite current multiplication level [19]. The breakdown voltage at higher dopant concentrations, in our case, are in closer agreement with the theoretical predictions by Sze and Gibbons [19].

The breakdown voltages at different doping concentrations reported by several authors [12,13,15,16] are in agreement; but some of their results are far from the theoretical curves predicted by Sze and Gibbons [19], Lee and Sze [25] and Okuto and Crowell [26], but are
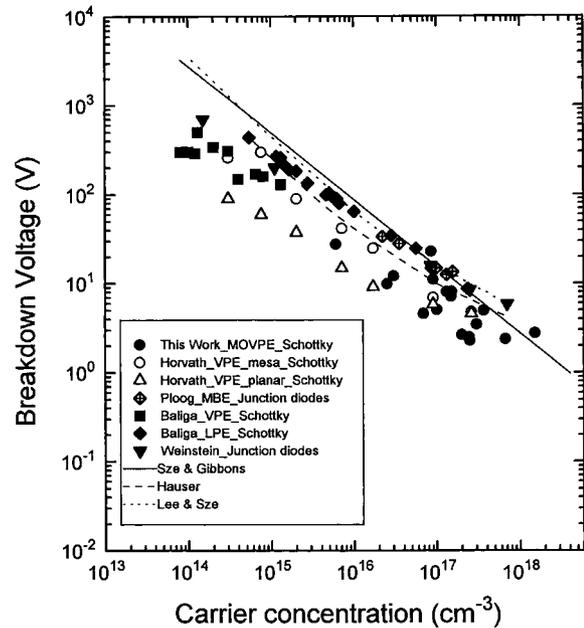
Fig. 1. Comparison of experimentally measured breakdown voltage of GaAs diodes with theoretical calculations published in the literature.

in closer agreement with Hauser's [27] calculations. As pointed out by Chynoweth et al. [28] and Moll [29] for junctions with breakdown at voltages less than 8 V for GaAs, the mechanism is mainly by tunneling, or direct field ionization of carriers. This breakdown voltage characteristics of Si-doped n-type GaAs is the extension of the V_{BD} at higher dopant concentrations. In this figure, the breakdown voltages obtained by other workers [11–13,15,16] in different growth techniques are also shown for comparison.

The maximum depletion layer width at breakdown calculated for the above epitaxial layers (both avalanche and Zener region) using Eqs. (1) and (3) is shown in Fig. 2. In Fig. 2, the theoretical curves published by Sze and Gibbons [19] and the experimental data published by other workers [11–13] in different growth techniques are also shown. From this figure it is seen that the depletion layer widths derived by several workers [12,13] are agreeing with each other except for the work done by Horvath et al. [11] in the vapor-phase (VPE) growth process of planar diodes. From Fig. 2 it can be concluded that a close agreement of the calculated maximum depletion layer width with the theoretical analysis of Sze and Gibbons [19] is established.

The maximum electric fields at breakdown voltages are also determined using the measured breakdown voltages and Eq. (1) for the diodes of different concentrations. These data are shown in Fig. 3 for compari-
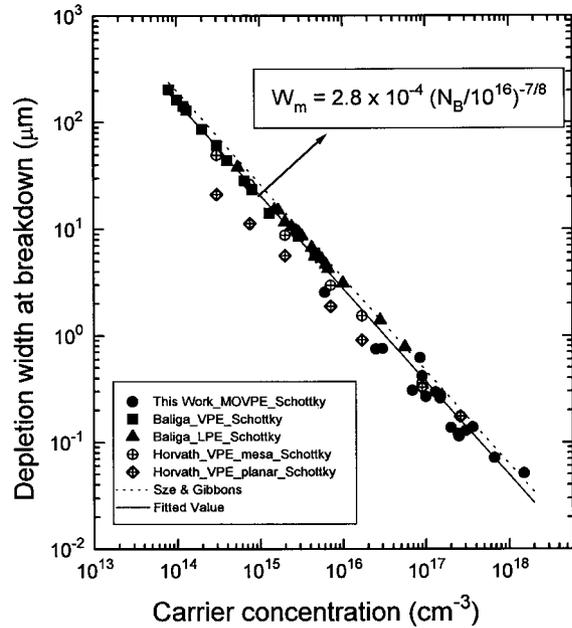
Fig. 2. Maximum depletion layer width at avalanche breakdown voltage of GaAs diodes as a function of carrier concentration.

Fig. 3. Maximum electric field strength at avalanche breakdown voltage as a function of carrier concentrations in GaAs.

son with the theoretical analysis of Sze and Gibbons [19]. The maximum electric field at breakdown increases with increasing carrier concentration because of a decrease in the avalanche path length [12]. It can also be seen from Fig. 3 that the maximum electric field is less compared to the theoretical predictions by Sze and Gibbons [19], although the depletion layer width is very close to the theoretical curves [19].

5. Conclusions

In conclusion, the breakdown characteristics of GaAs have been measured over carrier concentrations ranging from 6×10^{15} cm^{-3} to 1.5×10^{18} cm^{-3} using Au–Schottky barrier diodes formed on n-type GaAs layers grown by low pressure metal-organic vapor-phase epitaxial technique. The measured breakdown voltage is in close agreement with the theoretical curves predicted by Sze and Gibbons [19] in the higher concentration but there is a deviation in the low carrier concentrations. The maximum depletion layer width was found to be in good agreement with the theoretical curves predicted by Sze and Gibbons [19], while the maximum electric field has been found to be less in the lower concentrations. The results of this study on breakdown characteristics of GaAs are the extension of the V_{BD} characteristics measured by Baliga et al. [13] in the higher concentration range and it will be

useful for the design and development of GaAs switching devices as well as the design of the emitter-base region of bipolar transistors.

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