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Recent advances in diamond power semiconductor devices

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ABSTRACT

Diamond is known as an ultimate material because of its superior properties and it is expected to be employed in next-generation power electronic devices. Progress in epitaxial growth and fabrication techniques such as p- and n-type doping control with low compensation and surface treatment have improved the performance of power devices. High forward-current density and long-term stability have been achieved for Schottky barrier diodes operating at 400 °C. Fast turn-off operation with low loss and a high blocking capability of > 10 kV have also been realized. In addition, high blocking voltages of more than 2 kV have been achieved for switching devices such as metal-semiconductor field-effect transistors (MESFETs) and metal-oxide semiconductor FETs. To maximize device performance up to the material limit requires the development of fabrication techniques such as selective area doping, lithography, etching, formation of diamond/oxide interfaces and also defect reduction. Here, the current status of semiconductor diamond technology is reviewed.

1. Introduction

Diamond is a promising material for next-generation power electronics that offer low power consumption and high-frequency operation. High-temperature operation with a low leakage current is also expected because of its extremely low intrinsic carrier concentration and high built-in potential. Table 1 shows a comparison of the material properties of Si, 4H-SiC, GaN, Ga_2O_3 and diamond. Diamond has a high carrier mobility (4500 and 3800 cm^2/Vs for electron and holes, respectively) [1], a high breakdown field (> 10 MV/cm) [2], a low dielectric constant (5.7) and a very high thermal conductivity (2200 W/mK). Therefore, diamond based power devices are expected to significantly reduce both conduction and switching losses. The figure of merit (FOM) is one indicator of how much a device can be improved by using a particular material. Baliga introduced two important FOMs for high power devices: Baliga's FOM (BFOM) and Baliga's high-frequency FOM (BHFOM) [3]. The BFOM estimates the trade-off between conduction loss and breakdown voltage for a unipolar device, and the BHFOM includes the switching loss associated with the gate capacitance for a field-effect transistor (FET). Diamond exhibits values for both FOMs, as shown in Table 1. Huang also introduced the high-temperature FOM (HTFOM) and the chip-area FOM (CAFOM), which take into account the actual switching behavior and estimated high-temperature operation capability, and the reduction in chip area [4]. For both the HTFOM and the CAFOM, diamond has the best value for wide-gap materials.

In the present decade, diamond growth techniques have been improved and doping control methods for p, p+, n-type and intrinsic diamond have become available. The electrical properties of these materials can thus be characterized not only theoretically but also experimentally using device structures. The material properties of diamond that have be determined experimentally are indicated in italics with reference citations in Table 1. The carrier velocities of electrons and holes are estimated by the transient current technique [5] and also by the relationship between the gate length of FETs and the cut-off frequency (only holes) [6]. The carrier mobility is obtained by time-of-flight [1] and Hall effect measurements [7]. A maximum breakdown field of 9.5 MV/cm was reported by analysis of the doping profile and breakdown voltage for a planar Schottky barrier diode (SBD) [8]. Power device capabilities such as a high blocking voltage of $V_{max} > 10$ kV [9,10], high current operation at > 20 A [11], and fast operation with low-loss switching [12] have been recently reported for diamond SBDs. In this paper, recent progress in diamond semiconductor devices is reviewed.

2. Diamond devices

2.1. Diodes

Taking into account carrier activation and carrier scattering at room and elevated temperatures, the trade-off relationship between the on-resistance R_{on} and V_{max} for a unipolar diamond device can be obtained.

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Table 1
Material properties and FOMs for various semiconductors.

		Si	4H-SiC	GaN	Ga_2O_3	Diamond
Bandgap E_G [eV]		1.10	3.20	3.45	4.9	5.47
Saturation drift velocity v_S [x 10^7 cm/s]	Electron	1.1	1.9	2.5	2	2.5, *1.9* [5]
	Hole	0.8	1.2	–	–	1.0, *1.4* [5], *0.6* [6]
Carrier mobility μ [cm^2/Vs]	Electron	1500	1000	1500	300	*4500* [1],
	Hole	450	120	200	–	*3800* [1], *2000* [7]
Breakdown field E_{max} [MV/cm]		0.3	2.8	5	8	10–22, *9.5* [8]
Dielectric constant ε_r		11.9	9.66	8.9	9.93	5.7
Thermal conductivity λ [W/mK]		150	490	130	23	2200
Baliga's figure of merit (BFOM) $\varepsilon_r \mu E_{max}^3$		1.0	440	2950	3516	*473078 (3380)*
Baliga's high frequency FOM (BHFOM) μE_{max}^2		1.0	58	237	158	12510 *(1486)*
Huang's temperature FOM (HTFOM) $\lambda/\varepsilon_r E_{max}^2$		1.0	0.43	0.07	0.01	0.46 *(0.97)*
Huang's chip area FOM (HCAFOM) $\varepsilon_r \mu^{1/2} E_{max}^2$		1.0	58	192	280	3887 *(226)*

The total R_{on} of an SBD consists of the drift layer resistance R_{p-}, the parasitic resistance of the p+ layer R_{p+}, and the ohmic contact R_{Ohm}, as follows:

$$R_{on} = R_{p-} + R_{p+} + R_{Ohm} \tag{1}$$

For a one-dimensionally structured SBD, the total resistance R_{on} and specific on-resistance $R_{on}S$, can be expressed as:

$$R_{on} = \frac{d_{p-}}{p\mu qS} + \frac{\rho_{p+} d_{p+}}{S} + \frac{\rho_c}{S}, \tag{2}$$

$$R_{on}S = \frac{d_{p-}}{p\mu q} + \rho_{p+} d_{p+} + \rho_c, \tag{3}$$

where d_{p-}, d_{p+},p,μ_p,S,ρ_{p+}, andρ_c are the thicknesses of the p- and p+ layers, the carrier concentration in the p- layer, the mobility, contact area, resistivity of the p+ layer; and the specific contact resistance of the ohmic contact, respectively. The maximum blocking voltage V_{max} determined by avalanche breakdown for a unipolar diode can be expressed as:

$$V_{max} = E_{max} \bullet d_{p-} - \frac{qN_A d_{p-}^{\ 2}}{2\varepsilon_{dia}}, \tag{4}$$

where E_{max}, N_A, ε_{dia}, E_{max}, N_A, andε_{dia} are the avalanche breakdown field, acceptor concentration, and dielectric constant, respectively. The carrier concentration and mobility [13] are estimated using the following equations which take into account the temperature effect.

$$\frac{p \bullet (N_D + p)}{N_A - N_D - p} = \left(\frac{2\pi m^* kT}{h^2}\right)^{3/2} exp\left(-\frac{E_A}{kT}\right), \tag{5}$$

$$\mu = \frac{\mu_{max}}{1 + \left(\frac{N_A}{N_\mu}\right)^\gamma} \bullet \left(\frac{T}{300}\right)^{-\beta}, \tag{6}$$

$$\beta = \frac{\beta_{max}}{1 + \left(\frac{N_A}{N_\beta}\right)^\delta}, \tag{7}$$

Here, N_D, m^*,k,E_A $and \mu_{max}$ are the donor concentration in the drift layer, the effective mass of holes, the Boltzmann constant, the activation energy for boron, and the carrier mobility at low doping concentration, respectively. N_μ,N_β,β, $\gamma and \delta$ are the fitting parameters for the empirical mobility model. E_A is also a parameter dependent on N_A [14]. In this model, the doping dependence of E_{max} is not considered and is set to 10 MV/cm.

Fig. 1 shows the unipolar limit of $R_{on}S$ for Si, SiC [15,16] and diamond as a function of V_{max}. The unipolar limits for SiC and diamond at 250 °C are also indicated. The obtained limit is the so called Baliga limit without taking into account the switching losses. $R_{on}S$ for diamond is almost comparable to that for SiC at room temperature around V_{max} = 2 kV; however, it becomes almost one order of magnitude lower for devices with $V_{max} > 10$ kV. On the other hand, $R_{on}S$ lower by one to two orders of magnitude for all V_{max} values can be achieved at elevated temperatures. The optimum thickness and doping concentration for the drift layer at 1 and 10 kV are estimated through this analysis to be 1.7 µm with 1.1 × 10^{17}/cm^3, and 16 µm with 1.5 × 10^{16}/cm^3, respectively. The experimentally obtained $R_{on}S$ of diamond devices (open and solid circles in Fig. 1) are lower than the unipolar limit for Si and close to the SiC limit at present; however, these are still much higher than the expected characteristics for diamond. The reasons for the limitation will be discussed later but this is mainly due to (1) a low effective breakdown field strength because of field enhancement at the edge of the electrode, (2) an increase in leakage current through defects, and (3) non-optimized doping and thickness of the drift layers [17].

Both unipolar and bipolar diodes such as p-type-intrinsic-n-type diodes (PiNDs), SBDs, junction barrier Schottky diodes (JBSDs), metal-intrinsic-p type diodes (MiPDs), and Schottky pn diodes (SPNDs) have been experimentally reported. The cross-sectional structures and a summary of the device performance are listed in Table 2. The highest V_{max}, which is > 11.5 kV, has been obtained for a PiND without a mesa structure [10]. The breakdown voltage decreases because the leakage current increases when a mesa structure is utilized. The increase of the leakage current is considered to be due to defects formed during the mesa etching process. The forward current density for bipolar diamond devices is low because of the short minority carrier lifetime. The pseudo-vertical SBD (pVSBD) structure is well suited to diamond diodes

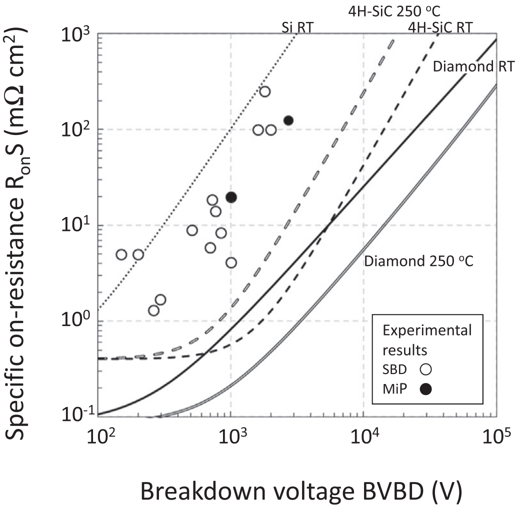

Fig. 1. Trade-off relationship between RonS and Vmax for unipolar devices on Si, SiC and diamond. Trade-off relationship on SiC and diamond at 250 °C are also indicated.

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