Relationship between Intrinsic Breakdown Field and Bandgap of Materials

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Abstract - A universal expression for the relationship between intrinsic breakdown field and bandgap of both semiconductors and insulators is proposed, and a quantitative criterion for distinguishing between semiconductors and insulators is introduced for the first time.

I. INTRODUCTION

For a high quality semiconductor or insulator material without defects and impurities, its theoretical intrinsic breakdown field E_{BI} should be a fixed value. However, the values of the breakdown field E_B of the same material given in the literatures are quite different due to the defects, composition mismatch and measurement errors. The maximum breakdown field E_{BM} obtained from the reported E_B data can be regarded as an approximate value of E_{BI}. The more perfect the material, the higher the breakdown field. So, E_{BI} should be higher than or equal to E_{BM}.

For semiconductors, there are some expressions for the relationship between critical field E_C (*i.e.* E_{BM}) and bandgap E_g. The expression $E_C = 1.02\times10^7\sqrt{(q/\varepsilon)N_B^{1/8}E_g^{3/4}}$ for abrupt junctions was derived based on the data of Si, Ge, GaAs and GaP only [1]. Recently, expressions E_{BM} (I) $= 1.73\times10^5\ E_g^{\,2}$ for indirect-gap semiconductors and E_{BM} (D) $= 2.38\times10^5\ E_g^{2.5}$ for direct-gap semiconductors have been derived by means of a least square method (LSM) to fit the E_{BM} data of thirteen different semiconductors for high-voltage device applications with very low doping concentrations, ignoring the impurity doping dependencies [2]. The two expressions can only give statistical results of the E_{BM} data at present, and should be revised with new data. So they can not well reflect the intrinsic breakdown characteristics. In addition, they are not applicable to insulators. Until now, no quantitative expression is available for insulators.

II. EXPRESSIONS FOR INTRINSIC BREAKDOWN FIELD

The E_{BM} data of fourteen commonly used elemental and binary compound semiconductors and eight binary insulators have been collected from the literatures. These data are listed in Tables I and II, respectively, and are plotted in Figure 1 together with the bandgap E_g. Diamond and AlN are plotted in Figure 1 as insulators since at room temperatures, undoped diamond and AlN are good insulators. We draw a thick dotted straight line through the higher data points of the insulators, and draw a thick solid straight line which passes through the E_{BM} point of silicon and is slightly above but as close as possible to the data points of the compound semiconductors. The two straight lines can be expressed by a universal expression

$$E_{BI} = 1.36\times10^7\,(E_g / 4.0)^{\alpha}\ (\text{V/cm}) \qquad (1)$$

where $\alpha = 3$ for semiconductors, and $\alpha = 1$ for insulators. So for semiconductors,

$$E_{BIS} = 1.36\times10^7(E_g/4.0)^3\ (\text{V/cm}) \qquad (2)$$

And for insulators,

$$E_{BII} = 1.36\times10^7(E_g/4.0)\ (\text{V/cm}). \qquad (3)$$

The difference of the power α values indicates that the breakdown mechanisms in semiconductors and insulators are different.

The universal expression (1) is applicable not only to both narrow and wide bandgap semiconductors, but also to insulators. This is the first time to propose a quantitative relationship between intrinsic breakdown field and bandgap of insulators.

From Figure 1 we can see that almost all the data points are located under the thick lines. This is reasonable. It means that the quality of these materials needs to be optimized to increase the breakdown field.

The expressions for the semiconductors in [2] are also plotted in Figure 1 as a comparison. We can see that many data points are located above their straight lines. This is the inevitable results of the LSM.

III. APPLICATIONS

A. A quantitative criterion for distinguishing between semiconductors and insulators

Resistivity ρ and bandgap E_g are usually used to define materials, but no unified criterion is available so far. For example, when ρ is used for semiconductors, Muller's criterion is 10^{-2} - 10^5 Ω-cm [3], Sze's is 10^{-3} - 10^8 Ω-cm [4], while Berger's is 10^{-5} - 10^{11} Ω-cm [5]. When E_g is used for insulators, Muller's criterion is $E_g > 5.0$ eV [3], while Quirk's is $E_g > 2.0$ eV [6].

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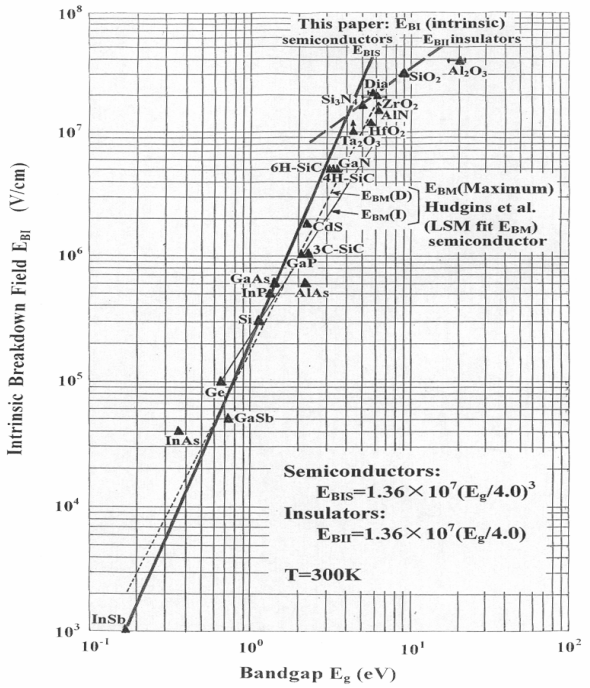

Fig. 1. Intrinsic breakdown field versus bandgap of semiconductors and insulators. The E_{BM} of a material is the maximum value available at present, while the E_{BI} of a material is a limit value, which shows the potential of the material.

From Figure 1 it can be seen that the distribution of E_{BI} *vs* E_g in the log-log plot is not continuous but forms two straight lines with different slopes, with semiconductors on one line and insulators on the other. The two straight lines intersect at E_g = 4.0 eV, which just divides the materials into two categories: the materials with $E_g < 4.0$ eV are semiconductors and those with $E_g > 4.0$ eV are insulators. It indicates that for either semiconductors or insulators, the intrinsic breakdown mechanism is closely related to the conductance mechanism, but the conductance mechanism, breakdown mechanism and E_{BM} *vs* E_g relationship of semiconductors are different from those of insulators.

To combine the above criterion with the criterion for metals, E_g = 0.0 eV, we can conclude that materials can be quantitatively classified by E_g into metals, semiconductors and insulators, i.e., *the materials with* E_g *at 0.0 eV are metals, those with* E_g *between 0.0 eV and 4.0 eV are semiconductors, and those with* E_g *higher than 4.0 eV are insulators.* This quantitative criterion can be called *breakdown field criterion* of materials,or simply, *Wang's criterion.*

Sometimes, the semiconductors with a very narrow bandgap, such as $E_g \leq 0.2$ eV, are called semimetals, and some insulators with the bandgap near 4.0 eV are called semiinsulators.

B. Material figures of merit expressed directly by E_g

By using the above expression for E_{BIS}, the figures of merit of semiconductors can be expressed directly by E_g (see Table III).

C. Prediction of E_{BI} *values of materials*

The E_{BI} values of many compound semiconductors and insulators have not been experimentally obtained and are usually difficult to measure, but their E_g values are already known or easy to measure, so it is of significance to predict the E_{BI} values of the interested materials. By using the above expressions, the E_{BI} values of many important elemental and compound semiconductors and high-*k* binary gate dielectrics have been calculated (see Tables IV and V).

The above expressions are also helpful for device simulation and theoretical derivation.

IV. CONCLUSION

1. A universal expression for the relationship between intrinsic breakdown field and bandgap of materials is proposed.

2. For both wide and narrow bandgap semiconductors, a more reasonable approximate expression for intrinsic breakdown field E_{BIS} is introduced.

3. For insulators, including high-k dielectrics, a quantitative relationship between intrinsic breakdown field and bandgap is proposed for the first time.

4. A quantitative criterion for classifying materials by their bandgap E_g, i.e., a breakdown field criterion, is proposed for the first time.

5. Simplified figures of merit of semiconductors expressed directly by bandgap E_g are given.

6. The values of the intrinsic breakdown field of many important binary compound semiconductors and high-k gate dielectrics are calculated.

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TABLE I

MAXIMUM BREAKDOWN FILED E_{BM} AND BANDGAP E_G OF THE SEMICONDUCTORS IN FIGURE 1 (T = 300 K)

Material [Data source]	InSb [7]	InAs [7]	GaSb [7]	Ge [7]	Si [7]	GaAs [11]	InP [7]	AlAs [9]	GaP [7]	SiC[7]			CdS	GaN [7]
										3C	6H	4H		
E_g (eV)	0.17	0.354	0.726	0.67	1.11	1.43	1.34	2.17	2.26	2.36	3.0	3.23	2.42 [8]	3.37
E_{BM} (MV/cm)	0.001	0.04	0.05	0.1	0.3	0.6	0.5	0.6	1.0	1.0	5	5	1.8 [10]	5

Data source: [7] *NCSR: National Compound Semiconductor Roadmap*, Available: www.ncsr.csci-va.com.
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TABLE II

MAXIMUM BREAKDOWN FIELD E_{BM} AND BANDGAP E_G OF THE DIELECTRICS (INSULATORS) IN FIGURE 1 (T = 300 K)

Material [Data source]	Ta_2O_5 [12]	HfO_2	ZrO_2 [15]	AlN	Diamond	Si_3N_4	SiO_2	Al_2O_3 (sapphire) [20]
E_g (eV)	4.2-4.3	5.65 [13]	5-7	6.23 [16]	5.46-6.4 [7]	5.0 [8]	9.0 [8]	18-23
E_{BM} (MV/cm)	>10	13 [14]	20	>15 [17]	21.5 [18]	16 [19]	30 [21]	39

Data source: [7] *NCSR: National Compound Semiconductor Roadmap*, Available: www.ncsr.csci-va.com.
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TABLE III

SIMPLIFIED FIGURES OF MERIT EXPRESSED DIRECTLY BY E_G

Figure of merit	Symbol	Expressed by E_{BI}	Expressed directly by E_g	Simplified figure of merit
Johnson's figure of merit [22]	JFOM	$\left(\frac{E_{BI}v_s}{2\pi}\right)^2$	$\frac{1.13\times10^{10}}{\pi^2}v_s^2E_g^6$	$v_s^2E_g^6$
Baliga's on-resistance figure of merit [23]	BFOM	$\varepsilon\mu E_{BI}^3$	$9.66\times10^5\varepsilon\mu E_g^9$	$\varepsilon\mu E_g^9$
Baliga's high frequency figure of merit [24]	BHFFOM	μE_{BI}^2	$4.54\times10^{10}\mu E_g^6$	μE_g^6
Huang's switching power figure of merit [25]	HMFOM	$E_{BI}\sqrt{\mu}$	$2.13\times10^5\sqrt{\mu}E_g^3$	$\sqrt{\mu}E_g^3$
Huang's chip size figure of merit [25]	HCAFOM	$\varepsilon E_{BI}^2\sqrt{\mu}$	$4.54\times10^{10}\varepsilon\sqrt{\mu}E_g^6$	$\varepsilon\sqrt{\mu}E_g^6$
Huang's heat dissipation figure of merit [25]	HTFOM	$\frac{\sigma_{th}}{\varepsilon E_{BI}}$	$\frac{\sigma_{th}}{2.13\times10^5\varepsilon E_g^3}$	$\frac{\sigma_{th}}{\varepsilon E_g^3}$
Gao-Morkoc's collector figure of merit [26]	Collector FOM	$v_S^{5/4}E_{BI}$	$2.13\times10^5(v_S^{5/4})E_g^3$	$v_S^{5/4}E_g^3$

Note: a) Since only the ratio of the figures of merit (FOMs) to that of silicon is usually used for material selection, we call the FOMs without the numeric constant simplified figures of merit.
b) σ_{th} is the thermal conductivity of a material.

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TABLE IV
PREDICTED INTRINSIC BREAKDOWN FIELD E_{BIS} VALUES OF IMPORTANT SEMICONDUCTORS (T = 300 K)
$E_{BIS} = 1.36\times10^7 (E_g/4.0)^3$ V/cm

Semiconductor	Ge	Si	SiC			AlSb	BP	GaN	GaSb	GaAs	GaP	InAs
			3C	4H	6H							
E_g (eV) [7, 8]	0.66	1.12	2.36	3.23	3.0	1.58	2.0	3.36	0.72	1.42	2.26	0.36
E_{BIS} (MV/cm)	0.061	0.30	2.80	7.18	5.75	0.84	1.70	8.08	0.08	0.61	2.46	0.01

Semiconductor	InSb	InP	CdS	CdSe	CdTe	ZnO	ZnS	PbS	PbTe	AlAs	AlP	ZnSe	ZnTe
E_g (eV) [7, 8]	0.17	1.35	2.42	1.70	1.56	3.35	3.68	0.40	0.31	2.16	2.45	2.7	2.25
E_{BIS} (MV/cm)	0.00105	0.52	3.02	1.05	0.81	8.01	10.6	0.014	0.0064	2.15	3.13	4.19	2.43

Data source of E_g: [7] *National Compound Semiconductor Roadmap*, Available: www.ncsr.csci-va.com.
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TABLE V
PREDICTED INTRINSIC BREAKDOWN FIELD E_{BII} VALUES OF SOME CANDIDATE HIGH-K BINARY GATE DIELECTRICS (T = 300 K)
$E_{BII} = 1.36\times10^7 (E_g/4.0)$ V/cm

High-k dielectric film	SiO_2	Si_3N_4	HfO_2	ZrO_2	Y_2O_3	Ta_2O_5	La_2O_3	Pr_2O_3	Gd_2O_3	Lu_2O_3
E_g (eV) [27, 28]	9.0	5.3	6.0	5.8	6.0	4.4	6.0	4.6	5.3	5.4
E_{BII} (MV/cm)	30.6	18.0	20.4	19.7	20.4	15.0	20.4	15.6	18.0	18.4

Data source of E_g: [27] J. Robertson, *J. Vac. Sci. Technol*., B18, p. 1785, 2000.
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