Breakdown voltage in thin III–V avalanche photodiodes

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The dead-space multiplication theory of Hayat and Saleh [J. Lightwave Technol. **10**, 1415 (1992)], in conjunction with the multiplication-width-independent ionization-coefficient model developed by Saleh *et al.* [IEEE Trans. Electron Devices **47**, 625 (2000)], are shown to accurately predict breakdown voltages for thin avalanche photodiodes of GaAs, InP, $In_{0.52}Al_{0.48}As$, and $Al_{0.2}Ga_{0.8}As$, over a broad range of device widths. The breakdown voltage is determined from the analytical expression for the impulse-response-function decay rate. © *2001 American Institute of Physics.* [DOI: 10.1063/1.1425463]

In recent years, there has been a considerable interest and a widespread research effort in the development of avalanche photodiodes (APDs) with thin multiplication layers, which have been shown to exhibit a significant reduction in gain fluctuations, commonly measured in terms of the excess noise factor.[1] The driving force behind this effort has been the need for high-sensitivity receivers in current lightwave communication systems that exploit the low-dispersion and low-loss windows of silica optical fibers, at 1.3 and 1.55 μm, respectively. The reduction in gain fluctuations in thin multiplication layers is principally attributable to the role played by carrier history:[2–13] After each impact ionization, an ionizing carrier must travel a minimum distance, called the dead space, before gaining enough energy to enable it to cause another impact ionization. The result is a spatial regularization of the impact ionizations which, in turn, leads to a reduction in the gain fluctuations.

In 1992, Hayat *et al.*[5–7] formulated a dead-space multiplication theory (DSMT) that permitted the gain, excess noise factor, gain probability distribution, and statistics of the time response of APDs to be calculated in the presence of dead space. This theory has recently been applied to experimental gain and excess-noise factor data for thin GaAs, InP, $In_{0.52}Al_{0.48}As$, and $Al_{0.2}Ga_{0.8}As$ APDs.[2,3] By developing a width-independent ionization-coefficient model, which used a special approach for fitting the data, Saleh *et al.*[3] obtained good agreement with the impact ionization and noise characteristics of devices fabricated from GaAs and $Al_{0.2}Ga_{0.8}As$ materials, over a broad range of multiplication-region widths. Similar ionization-coefficient models were also extracted for InP and $In_{0.52}Al_{0.48}As$ materials.[4] The DSMT has also been successfully applied to experimental data by different approaches for fitting the data.[2,11,12] In all cases, the results are superior to those obtained using conventional multiplication theory.[14]

For APDs with thin multiplication layers, the significance of dead space on the multiplication characteristics makes it important to include dead space in determining the value of the breakdown voltage. In this letter, we use the DSMT and the width-independent ionization-coefficient model to calculate the avalanche breakdown voltage, V_B, for homojunction APDs fabricated from the same four materials: GaAs, InP, $In_{0.52}Al_{0.48}As$, and $Al_{0.2}Ga_{0.8}As$. We show excellent agreement with experiment, and thereby further demonstrate the predictive capabilities of the DSMT/ionization-coefficient models for accurately determining breakdown voltage, as well as the gain and excess noise factor as demonstrated previously.

The voltage V_B is defined as the reverse-bias voltage across the multiplication region at which the mean gain becomes infinite. Since an explicit formula for the gain is not available in the context of the DSMT, we instead turn to the closed-form expression for the asymptotic exponential decay rate of the mean impulse response function derived by Hayat and Saleh.[7] The rationale for using this approach is as follows: the presence of the exponentially decaying tail of the mean impulse response function implies a finite area under the curve; this, in turn, implies a finite mean gain since the area under the mean impulse response is proportional to the mean gain. The reverse-bias voltage at which the decay rate becomes zero, and thus at which the gain becomes infinite, is then precisely the breakdown voltage V_B.

When an electron (or hole) initiates the multiplication process, an electric current is induced by the moving electrons and holes within the multiplication region. This current comprises the random buildup-time-limited impulse response function, $I(t)$. It has been shown in Ref. 7 that there exists a

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TABLE I. Parameters of the width-independent DSMT exponential-ionization-coefficient model, obtained[a] for GaAs, InP, $In_{0.52}Al_{0.48}As$, and $Al_{0.2}Ga_{0.8}As$ thin APD structures. The electron and hole ionization threshold energies are also provided.

		Units	GaAs	InP	$In_{0.52}Al_{0.48}As$	$Al_{0.2}Ga_{0.8}As$
α	A	cm^{-1}	6.01×10^6	3.01×10^6	4.17×10^6	5.39×10^6
	$\mathcal{E}_c$	V/cm	2.39×10^6	2.45×10^6	2.09×10^6	2.71×10^6
	m		0.90	1.08	1.20	0.94
β	A	cm^{-1}	3.59×10^6	4.29×10^6	2.65×10^6	1.28×10^6
	$\mathcal{E}_c$	V/cm	2.26×10^6	2.08×10^6	2.79×10^6	2.06×10^6
	m		0.92	1.12	1.07	0.95
E_{ie}		eV	1.90	2.05	2.15	2.04
E_{ih}		eV	1.55	2.20	2.30	2.15

[a]See Ref. 4.

constant γ, which depends on the electron and hole ionization coefficients α and β, the electron and hole dead spaces d_e and d_h, the electron and hole saturation velocities within the multiplication layer, and the multiplication-layer width w, such that the mean of $I(t)$ satisfies $\lim_{t\to\infty}\langle I(t)\rangle e^{\gamma t} = \text{constant}$. This means that asymptotically, $\langle I(t)\rangle \sim e^{-\gamma t}$. For a stable device, the rate γ must be strictly positive to insure exponential decay and hence finite gain. At the precise threshold of V_B, γ becomes zero. Now, it has been shown in Ref. 7 that $\gamma=0$ *if and only if*

$$e^{(r_1-r_2)(w-d_h)}(r_2+2\alpha e^{d_e r_2}-\alpha)=r_1+2\,\alpha\,e^{d_e\,r_1}-\alpha, \tag{1}$$

where r_1 and r_2 are the two roots of the following transcendental equation:[7]

$$(r+2\alpha e^{d_e r}-\alpha)(r-2\beta e^{-r d_h}+\beta)+\alpha\beta e^{r(d_e-d_h)}=0. \tag{2}$$

The aforementioned stability condition is also valid for hole-injection APDs (e.g., InP) with the proviso that the roles of electrons and holes are interchanged in Eqs. (1) and (2).

For each type of material, the device parameters d_e, d_h, α, and β, are functions only of the electric field $\mathcal{E}$ in the multiplication layer.[3] In particular, $d_e=E_{ie}/q\mathcal{E}$ and $d_h=E_{ih}/q\mathcal{E}$, where E_{ie} and E_{ih} are the electron and hole ionization threshold energies, respectively, and q is electron charge. Furthermore, α and β are modeled by exponential functions of the electric field: $\alpha(\mathcal{E}),\ \beta(\mathcal{E})=A\exp[-(\mathcal{E}_c/\mathcal{E})^m]$. The sets of parameters associated with this exponential model were determined in accordance to a modified version (from Ref. 4) of the method reported in Ref. 3 for the four materials under consideration. They are provided for convenience in Table I, along with the values for E_{ie} and E_{ih} that emerge. These parameters were selected to produce the best fit to excess noise data.

Thus, by solving for the particular voltage across the multiplication region, $w\mathcal{E}(w)$, at which Eq. (1) becomes zero, we determine V_B for all four materials, as predicted by the dead-space multiplication theory. In each case, the correctness of the calculated V_B was checked by plotting the mean gain (obtained by solving certain recurrence equations numerically)[3,5] as a function of the applied electric field and determining the breakdown electric field at which the gain becomes infinite. We emphasize at this point that the calculation of the breakdown voltage directly from Eq. (1) is much more computationally efficient and accurate than using gain versus $\mathcal{E}$ plots. The experimental values of V_B were obtained by gradually increasing the reverse-bias voltage until breakdown occurred. The details of the devices and experimental procedures were reported in Ref. 2. The predictions of V_B are compared with the experiment in Fig. 1 for GaAs and InP, and in Fig. 2 for $In_{0.52}Al_{0.48}As$ and $Al_{0.2}Ga_{0.8}As$, all as a function of the multiplication-layer

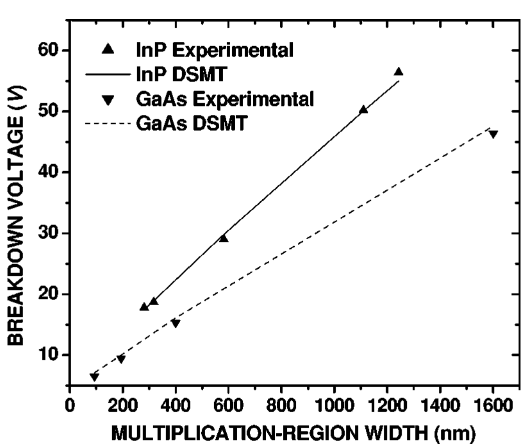

FIG. 1. Experimentally measured breakdown voltage V_B versus multiplication-region width w for InP (triangles) and GaAs devices (inverted triangles). Predictions based on the DSMT are shown as solid and dashed curves for InP and GaAs, respectively.

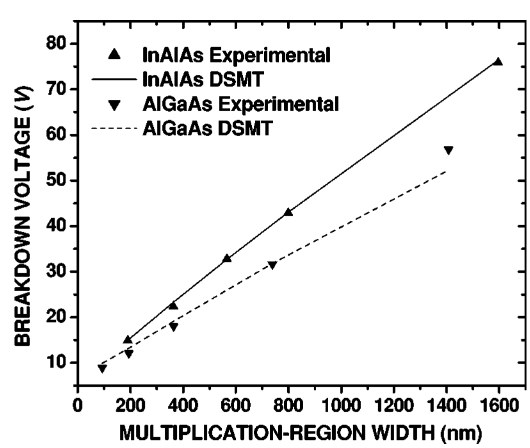

FIG. 2. Experimentally measured breakdown voltage V_B versus multiplication-region width w for $In_{0.52}Al_{0.48}As$ (triangles) and $Al_{0.2}Ga_{0.8}As$ devices (inverted triangles). Predictions based on the DSMT are shown as solid and dashed curves for InAlAs and AlGaAs, respectively.

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width w. It is evident that the DSMT predictions are in excellent accord with the data for the entire range of device widths over which measurements were made, from 100 to 1600 nm.

It has been previously observed by several groups that the breakdown (BD) electric field, $\mathcal{E}_{\mathrm{BD}}(w)=V_B/w$, becomes higher as the multiplication-layer width is reduced.[2] An analytical description of this phenomenon can be established as follows: Observe that the nearly straight-line behavior of the data and the DSMT curves in Figs. 1 and 2 (i.e., $V_B=a+bw$) indicates that $\mathcal{E}_{\mathrm{BD}}$ can be approximated by $\mathcal{E}_{\mathrm{BD}}(w)=aw^{-1}+b$. For example, for GaAs, $a\approx 3.74$ V and $b\approx 2.81\times 10^5$ V/cm. This simple model for $\mathcal{E}_{\mathrm{BD}}$ can be used for the easy calculation of the breakdown electric field for any w within the range 100–1600 nm.

In this letter we followed the commonly accepted assumption that the electric field is uniform across the multiplication layer.[7] To extend our treatment to nonuniform fields, the recurrence equations for the impulse response,[7] which is central to this letter, must be generalized to nonuniform fields (as the gain and the excess-noise-factor theory was extended to nonuniform fields by Hayat *et al.*[6] and later by McIntyre)[11]. However, the derivation of a closed-form solution for the breakdown condition, as given in Eq. (1), may no longer be possible for the general case. Alternative approaches for finding the breakdown voltage for nonuniform fields would be to invoke the gain versus reverse-bias-voltage characteristics using the theory reported in Refs. 6 or 11. Another possibility is to numerically solve McIntyre's recursive equations for the breakdown-voltage probabilities.[11] Both of these alternative approaches, however, are computationally intensive since they would involve computing recursive equations near the breakdown condition.

We make the final comment that because the successful prediction of the breakdown voltage in thin APDs has been achieved in the context of an impulse-response-based, rather than a gain-based approach, the approach developed here will find use for predicting the frequency–response characteristics of thin APDs, which will be considered elsewhere.

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