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Optimized Breakdown Probabilities in Al/sub 0.6/Ga/sub 0.4/As-GaAs Heterojunction Avalanche Photodiodes

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Abstract

Recently, it has been shown that the noise characteristics of heterojunction Al/sub 0.6/Ga/sub 0.4/As-GaAs avalanche photodiodes (APDs) can be optimized by proper selection of the width of the Al/sub 0.6/Ga/sub 0.4/As layer. Similar trends have also been shown theoretically for the bandwidth characteristics. The resulting noise reduction and potential bandwidth enhancement have been attributed to the fact that the high bandgap Al/sub 0.6/Ga/sub 0.4/As layer serves to energize the injected electrons, thereby minimizing their first dead space in the GaAs layer. We show theoretically that the same optimized structures yield optimal breakdown-probability characteristics when the APD is operated in Geiger mode. The steep breakdown-probability characteristics, as a function of the excess bias, of thick multiplication regions (e.g., in a 1000-nm GaAs homojunction) can be mimicked in much thinner optimized Al/sub 0.6/Ga/sub 0.4/As-GaAs APDs (e.g., in a 40-nm Al/sub 0.6/Ga/sub 0.4/As and 200-nm GaAs structure) with the added advantage of having a reduced breakdown voltage (e.g., from 36.5 V to 13.7 V).

Avalanche PHOTODIODES (APDs), when operated in a Geiger mode as single-photon counters, often offer many advantages over photomultiplier tubes. These include higher quantum efficiency, smaller size, lower breakdown voltage, and insensitivity to magnetic fields [1]. In Geiger-mode operation, an APD is reverse-biased above avalanche breakdown so that each photo-excitation results in, with a certain field-dependent probability, an avalanche breakdown. This, in turn, yields a measurable electric current. Subsequently, the APD is quenched by an external circuit, readying it for the next incoming photon [2].

Generally, as the applied reverse-bias voltage is raised beyond a breakdown threshold, called the breakdown voltage (V_{BR}), the probability of an infinite multiplication factor ascends from zero and gradually approaches unity as a function of the applied voltage [3]. The characteristics of the breakdown probability as a function of the beyond-breakdown excess reverse-bias voltage $\Delta V = V - V_{BR}$ is the key indicator of how rapidly the transition from stable (finite gain) to saturated operation (infinite gain) occurs. Clearly, since the dark-current-generation rate increases with the field, it is most desirable to have the transition from stable to saturation occur with as little excess-bias voltage as possible.

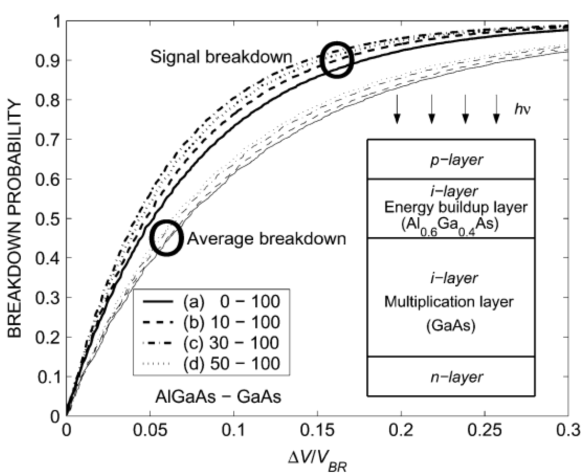

Fig. 1. Breakdown probability of a 100-nm GaAs with (a) no $Al_{0.6}Ga_{0.4}As$ layer (solid), (b) a 10-nm $Al_{0.6}Ga_{0.4}As$ layer (dashed), (c) a 30-nm $Al_{0.6}Ga_{0.4}As$ layer (dashed-dotted), and (d) a 50-nm $Al_{0.6}Ga_{0.4}As$ layer (dotted). The parameters used in calculating the ionization coefficients and the threshold energies are taken from [15] for $Al_{0.6}Ga_{0.4}As$ and from [16] for GaAs. Thin curves represent the average breakdown probability caused by randomly-distributed dark carriers. The inset depicts the schematic of the structure. Note that this is a simplified schematic illustrating only multiplication region of a SAM APD.

Recently, analytical simulations have shown that certain optimized APDs with double-layered $Al_{0.6}$ $Ga_{0.4}$ As–GaAs heterojunction multiplication regions exhibit significantly reduced excess noise factors [4], [5] as well as enhanced gain-bandwidth products (GBP) [6]. The noise reduction and possible GBP enhancement are attributed to the combination of the initial-energy effect and the boundary effect [4]–[5][6], both of which are related to the spatial modulation of the carriers' dead spaces. The initial energy refers to the finite energy that injected carriers may possess before entering the multiplication region. Such an energized carrier exhibits a strong tendency to cause an initial ionization event near the edge of the multiplication region, as the initial energy tends to minimize the first dead space. The boundary effect refers to scenarios in heterojunction two-layer multiplication regions for which carriers crossing the layers' boundary experience a sudden drop in the ionization threshold energy. Certain carriers that have not yet acquired sufficient energy to become capable of ionizing inside the high bandgap material (e.g., in $Al_{0.6}$ $Ga_{0.4}$ As) may become capable of ionizing as soon as they enter the material with lower bandgap (e.g., GaAs). In effect, the high-bandgap material serves as an energy-buildup layer, elevating the energy of injected carriers before they cross into the low bandgap layer, where the bulk of the ionizations take place. By carefully designing the width of the energy-buildup layer, the heterojunction APDs can exhibit significant reduction in the excess noise factor and enhanced GBP [5], [6]. Such noise reduction in AlGaAs–GaAs heterojunction APDs has already been observed experimentally and by Monte Carlo simulation [7], [8]. However, experimental verification of the GBP enhancement is not yet available.

We have previously shown analytically that the increase in the breakdown-probability becomes more steep, as a function of the excess-bias voltage, when the injected carriers possess an initial energy prior to entering the multiplication region [3]. In this letter, we show that a similar increased steepness occurs by using the $Al_{0.6}$ $Ga_{0.4}$ As–GaAs heterojunction multiplication-region structure reported in [5]. Moreover, the breakdown-probability characteristics of the heterojunction APDs can be optimized through the selective choice of the width of the $Al_{0.6}$ $Ga_{0.4}$ As energy-buildup layer. We emphasize that the primary goal of this letter is to demonstrate the idea of enhancing and optimizing the breakdown-probability characteristics by means of utilizing heterojunction multiplication-region structures.

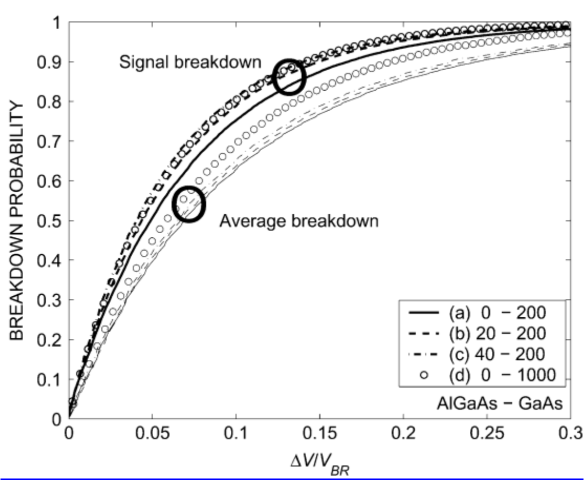

Fig. 2. Breakdown probability of 200-nm GaAs with (a) no $Al_{0.6}$ $Ga_{0.4}$ As layer (solid), (b) a 20-nm $Al_{0.6}$ $Ga_{0.4}$ As layer (dashed), (c) a 40-nm $Al_{0.6}$ $Ga_{0.4}$ As layer (dashed-dotted), (d) a 1000-nm homojunction GaAs (∘). Thin curves represent the average breakdown probability caused by randomly-distributed dark carriers.

To characterize the breakdown probability, we will use the recurrence technique developed by Hayat et al. [3], which generalized McIntyres history-dependent theory for the breakdown probability [9] to heterostructure APDs with the inclusion of any initial energy for injected carriers. We begin by demonstrating the validity of our model by comparing our predictions of the breakdown voltages for a series of 100- to 1600-nm homojunction

GaAs APDs with the experimental measurements reported by Yuan et al. [10]. The predicted breakdown voltages for a 100-, 200-, 400-, and 1600-nm homojunction GaAs APDs are 7.08, 10.2, 16.1, and 46.7 V, respectively. The corresponding experimental values are 6.7, 9.8, 15.4, and 46.2 V, respectively. In all cases, our predictions are within approximately 5% of their measured counterparts.

Next, we predict the breakdown characteristics of double-layered $Al_{0.6}Ga_{0.4}As$–GaAs heterojunction multiplication-layer APDs (shown by the inset in Fig. 1). In this letter, we will assume a separate-absorption-multiplication (SAM) structure for which the absorption of incident photons takes place in a different intrinsic layer (not shown in Fig. 1). Figs. 1 and 2 show the breakdown probability curves as a function of the normalized excess voltage, Δ*V*/*V*BR. In Fig. 1, the width of the GaAs layer is fixed at 100 nm, while the width of the $Al_{0.6}Ga_{0.4}As$ layer is varied. As shown in the figure, the steepness increases as the width of the $Al_{0.6}Ga_{0.4}As$ layer grows larger until it reaches 30 nm, which results in the maximum steepness. The steepness is reduced, however, as the $Al_{0.6}Ga_{0.4}As$ layer width is further increased beyond 30 nm. A similar phenomenon is observed for the fixed 200-nm GaAs APDs (Fig. 2) as the steepness increases until the $Al_{0.6}Ga_{0.4}As$ layer width reaches 40 nm. As described earlier, through bandgap engineering the combination of the initial energy and the heterojunction-boundary effects tends to bring the location of the first ionization of injected carriers closer to the boundary [4]–[5][6]. To see the extent of this effect on the breakdown-probability enhancement, consider the hypothetical ideal scenario in which the first ionization occurs precisely at the boundary, whereby the injected electron into the GaAs layer is instantly replaced by two electrons. Let *P*1 denote the breakdown probability resulting from one electron injected into a single GaAs layer, and let *P*2 denote the breakdown probability when two electrons are simultaneously activate the avalanche process. A simple calculation shows that *P*2≥1−(1−*P*1)2, which implies that *P*2>*P*1. (Note that the first inequality is an equality if the secondary ionizations in the $Al_{0.6}Ga_{0.4}As$ layer are neglected). Indeed, Fig. 1 confirms that the breakdown probability curves for all heterostructures lie below *P*2. Clearly, since in the heterostrucures the first ionization occurs at a random (finite) distance from the $Al_{0.6}Ga_{0.4}As$–GaAs boundary, according to an exponential probability density function, the *P*2 upper bound is not attained.

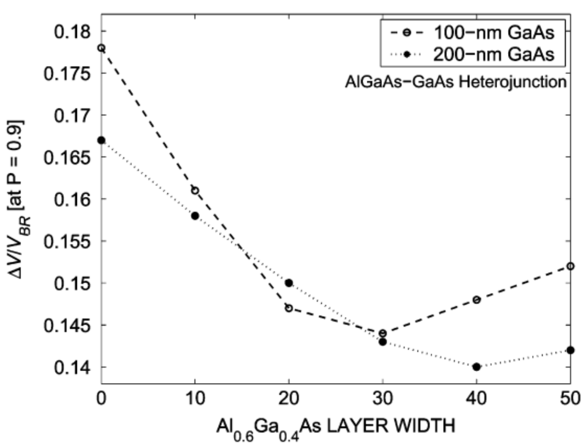

Fig. 3. Normalized excess voltage Δ*V*/*V*BR for achieving a breakdown probability of 0.9 as a function of the $Al_{0.6}Ga_{0.4}As$ layer width. The dashed curve with open circles (∘) represents the 100-nm GaAs APD and the dotted curve with closed circles (·) represents the 200-nm GaAs APD.

As a means of quantifying the steepness characteristics, the normalized excess voltages (Δ*V*/*V*BR) are measured for the breakdown probability of 0.9, as depicted in Fig. 3. As shown in the figure, Δ*V*/*V*BR reaches its minimum at 30 nm in the 100-nm GaAs-layer case and at 40 nm for the 200-nm GaAs-layer case. The reductions in Δ*V*/*V*BR (compared to a homojunction GaAs APD) for the 100-nm GaAs-layer and 200-nm GaAs-layer cases are 19.1% and 14.4%, respectively. Interestingly, these optimum structure configurations (i.e., the 30-nm $Al_{0.6}Ga_{0.4}As$—

100-nm GaAs and the 40-nm $Al_{0.6}$ $Ga_{0.4}$ As—200-nm GaAs structures) coincide with the configurations that minimize the excess noise factor [5] and maximize the GBP [6].

It is known that as the width of multiplication region increases in a homojunction APD, the steepness of the breakdown probability curves becomes sharper [1], which indicates that the thick devices exhibits better detection efficiency. In contrast, as shown in Fig. 2, the optimized heterostructure APD with a 40-nm $Al_{0.6}$ $Ga_{0.4}$ As—200-nm GaAs two-layer multiplication region exhibits the steepness equivalent to a 1000-nm homojunction GaAs APD. Additionally, the optimized heterostructure admits a substantially lower operating voltage (from approximately 36.5 V for a 1000-nm homojunction to 13.7 V for the optimized heterojunction APD).

To evaluate the breakdown characteristics due to dark current generated in the high-field multiplication region, we calculated the average breakdown probability induced by thermally generated or trapped carriers inside the multiplication region. We assume that the dark electrons and holes are distributed randomly throughout the multiplication region (including the buildup layer). As shown in Fig. 1 (thin curves), the average breakdown probability of the optimized structure (i.e., 30-nm $Al_{0.6}$ $Ga_{0.4}$ As—100-nm GaAs) is not maximized. Also, as shown in Fig. 2 (thin curves), the average breakdown probability of the optimized structure (i.e., 40-nm $Al_{0.6}$ $Ga_{0.4}$ As—200-nm GaAs) is much less than a 1000-nm homojunction GaAs APD. Thus, we may argue that the optimized structures improve the signal breakdown probability while suppressing the average breakdown probability. This result is a consequence of the dependence of the breakdown probability on the position of the parent carrier (these probabilities can be calculated using the recurrence relation described in [3]. It must be noted, however, that the probability of hole trapping may increase in a heterojunction multiplication region. This can aggravate the after-pulsing phenomenon encountered in gated photon counting.

In summary, we have theoretically shown that the desirable breakdown-probability characteristics of a thick multiplication region homojunction GaAs APD can be mimicked in an optimized and much thinner heterojunction multiplication region with the added advantage of reduced breakdown voltage. We emphasize that we have not assumed any ionization-enhancement effects resulting of the band-edge discontinuity at the hetero-interface. (A number of recent Monte Carlo studies on $Al_{0.6}$ $Ga_{0.4}$ As–GaAs multilayers predict no such ionization enhancement [11]–[12][13][14].) Interestingly, the same optimized structures that yield the best breakdown-probability characteristics give the least predicted excess noise factor and maximum GBP when operated in a linear mode.

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