Quasi-Direct UV/Blue GaP Avalanche Photodetectors

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***Abstract*—GaP avalanche photodiodes, with thin device layers have been processed, utilizing both p-i-n and recessed window p-i-n structures, as well as a Schottky structure. The results showed low dark currents, good quantum efficiency (QE), and high gains up to 10^3, with good uniformity across the wafer. The peak QE at 440 nm indicated Γ-valley absorption, rather than band-edge absorption. The recess window photodiodes exhibited enhanced UV detection as a result of reduced absorption and recombination in the undepleted p-layer. Additionally, the Schottky structure demonstrated potential for further enhanced UV detection, by employing a thin semitransparent contact.**

***Index Terms*—Avalanche photodiodes, photodetectors, ultraviolet.**

I. Introduction

GALLIUM phosphide, though most commonly used in emitters, has potential for use in both ultraviolet and blue light detection applications from 250 to 500 nm. Detection of these wavelengths has medical, military, and environmental applications. The primary application of interest is biological agent detection, which requires three different detector wavelength ranges. The first collects UV (300–400 nm) signals primarily from tryptophan ($\sim$330 nm). The second detects visible (400–600 nm) fluorescence from NADH and flavin compounds, and the third senses scattered light at the 266-nm excitation wavelength [1].

Currently, photomultiplier tubes (PMTs) fill this niche due to their high responsivity, high internal gain ($> 10^6$), and low noise. However, they are large, fragile, and require high bias voltages. This leaves an opening for alternative semiconductor technologies. Current research thrusts are AlGaN/GaN and SiC photodiodes. AlGaN/GaN devices are attractive for their solar-blind cutoff (<290 nm) for 266-nm applications, but high defect densities ($\sim$109 cm^{-2}), localized microplasma breakdown, and premature edge breakdown preclude high avalanche gain [2]–[4]. SiC devices, with a visible-blind cutoff (<380 nm), have achieved low noise and high gain, but their high cost and high breakdown field ($\sim 4 \times 10^6$ V/cm) leave room for competitive material systems [5].

GaP is often overlooked for UV applications due to its indirect band gap of 2.26 eV, corresponding to a wavelength of 550 nm. However, GaP has much higher absorption coefficients at shorter wavelengths [6]. This attribute can be exploited by using absorption layers thinner than the absorption length necessary for photoresponse at longer wavelengths, corresponding to the indirect band gap. This allows the Γ-valley energy gap of 2.78 eV to dominate the photoresponse. Schottky photodiodes have utilized this increased absorption at shorter wavelengths, where device operation occurs near the surface of the device. Though some UV GaP Schottky photodiodes are already on the market [7], none report gain, which is necessary for many UV applications, as well as being a competitive alternative to PMTs.

On the other hand, GaP avalanche photodetectors (APDs) will require more expensive filters than SiC or AlGaN–GaN due to their higher response in the visible spectrum. This aspect combined with their lower response in the deep UV makes these devices, in their present form, more suitable for the 400–600-nm band discussed above. Though SiC enjoys a much higher gain than either GaP or AlGaN–GaN, GaP has a significantly higher gain than AlGaN–GaN, a much lower cost than SiC, and with further device engineering, can achieve improved deep UV response.

This paper discusses the results of GaP APDs that employ thin device layers in order to utilize the high absorption coefficients of GaP at short wavelengths. These devices have attained high gain, low dark current, and good quantum efficiency (QE).

II. Material Structure and Device Fabrication

Three device structures were processed and characterized for this study. The first two were from the same wafer and consisted of a p-i-n structure grown on a thin semi-insulating layer on an n-type GaP substrate. The thickness of the p, i, and n layers are 300 nm, 300 nm and 500 nm, respectively. The dopant concentration was 2×10^{18} cm^3 for the n-type layer. The dopant concentration of the p-layer was graded from 2×10^{18} cm^3 at the p-i interface to 2×10^{19} cm^3 at the top surface.

The device fabrication employed standard photolithography for all three mask layers. An etchant consisting of equal parts $HNO_3 : HCl{:}H_2O$ defined the mesas [8]. Next a SiO_2 passivation layer was deposited via plasma-enhanced chemical-vapor deposition (PECVD). Contacts were then formed on the devices using electron-beam evaporation and a standard liftoff process. The n-type contacts consisting of AuGe–Ni–Au were evaporated onto the device followed by a 30-s anneal at 430 °C. Finally, Ni–Au p-type contacts were applied to yield a device with a cross section as in Fig. 1(a), which will be referred to as the standard device. Fig. 1(b) shows the device cross section of additional devices fabricated using a recessed window structure that reduced the p-type layer by 700 Å in the window [9].

The third device was fabricated from a Schottky wafer, which consisted of an n-type substrate with a thin semi-insulating buffer layer, followed by an n-i-p-i structure. The layer

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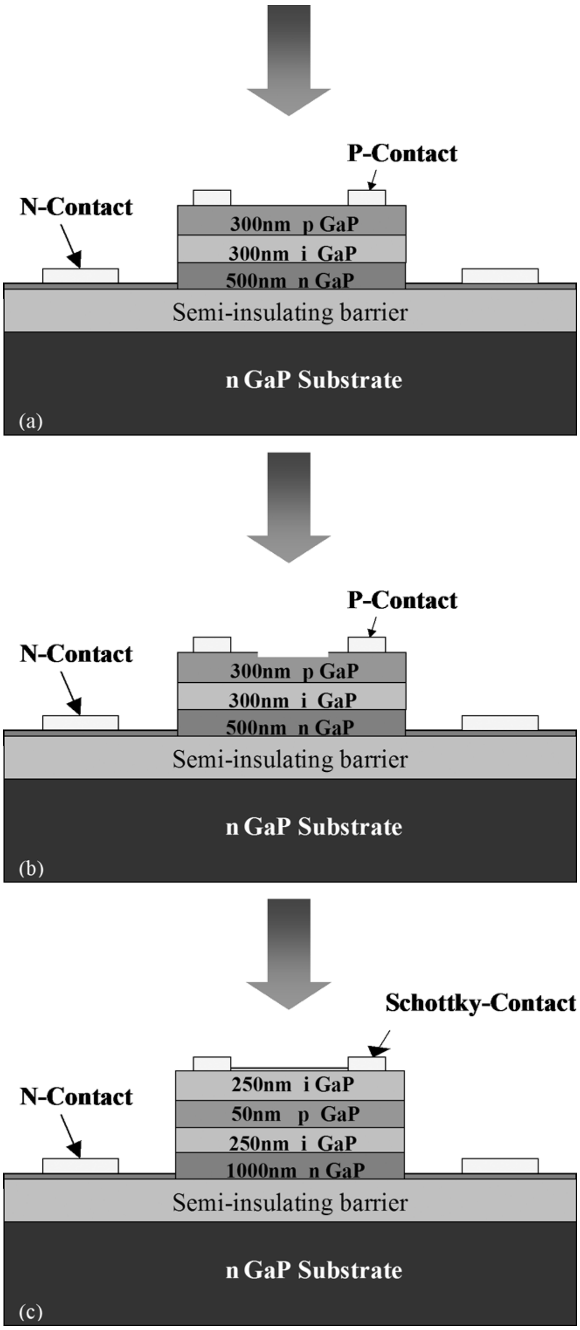


Fig. 1. Cross section of GaP APD. (a) Standard. (b) Recessed window APD. (c) Schottky.

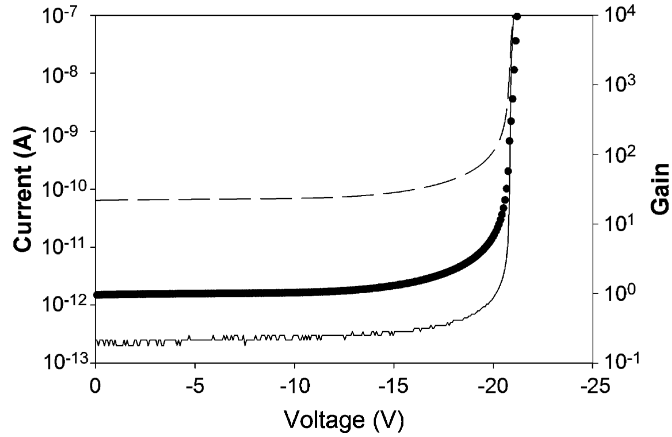


Fig. 2. I–V characteristic for an 80 μm diameter device. I–V curves were the same for both standard and recessed window APDs.

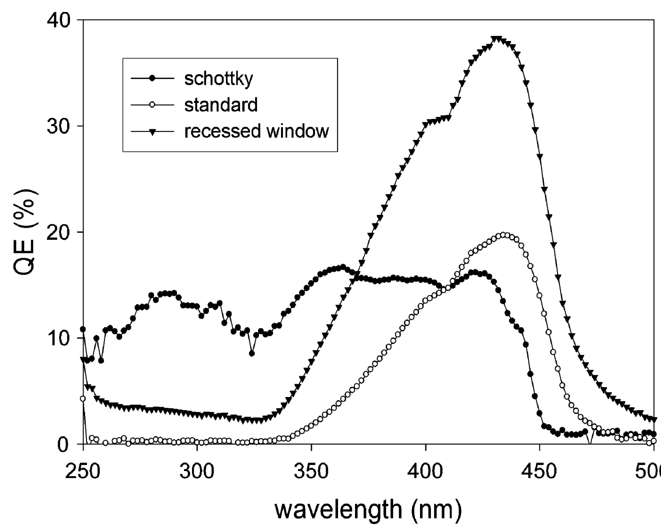


Fig. 3. QE of a standard GaP APD, a recessed window GaP APD, and a Schottky photodiode, measured at unity gain.

thickness was 1000, 100, 50, and 250 nm, respectively, with a doping concentration of 1×10^{18} cm^3 for both the n and p layers. Device processing was the same as for the standard devices, with a thin, semitransparent metal contact covering the mesa, as shown in Fig. 1(c) [10]. The Schottky contacts were Ti–Au, and the thin metal was 100 Å Au. Only the unity gain QE characteristics of the Schottky devices will be discussed, since theses devices were p-i-n diodes, not APDs.

III. Current–Voltage Characteristics

Fig. 2 shows the I–V characteristics for both standard and recessed window devices, which demonstrated identical I–V characteristics. At unity gain ($\sim$10 V) both devices demonstrated low dark currents, less than 1 pA, uniformly across the samples. Devices ranging from 80 to 250 μm exhibited low dark current densities < 1 nA/cm^2 at unity gain, which was comparable to previous reports of dark current in GaP devices [11].

The dark current and photoresponse remained flat with little dependence on bias voltage prior to the onset of avalanche multiplication. The photoresponse of both devices was measured using a broadband UV lamp and an HP4145 parameter analyzer. The breakdown voltage was $\sim$21 V. Both devices showed gains of 10^2–10^3.

IV. Quantum Efficiency

Fig. 3 shows the spectral response, for all three photodiodes at unity gain, measured with a xenon lamp source, a monochromator, and a lock-in amplifier. The peak QE for both the standard and recessed window GaP APDs at a wavelength of $\sim$440 nm confirmed that the strongest absorption occurred at wavelengths corresponding to the Γ-valley bandgap, as intended by using thin device layers. The nonrecessed window device had a peak QE of only 20% and a spectral range extending from 350 to 475 nm.

In GaP, shorter wavelengths have a higher absorption coefficient and consequently a shorter absorption length. Therefore, increased QE in the UV spectrum hinges on these carriers reaching the active region prior to recombination. Also, by shortening the overall thickness of the device, absorption at longer wavelengths was reduced. It follows that additional reduction of the p-region thickness would further increase the QE in the ultraviolet range, thus a recessed window structure was implemented.

Fig. 3 shows the spectral response, where the recessed window depth was ~ 700Å. An improved peak QE occurred at ~440 nm, as well as an enhanced QE at wavelengths below 350 nm, the lower spectral range limit of the standard devices.

The external QE was modeled using the same approach as in [12]. This simulation predicted an increase in the QE at UV wavelengths and indicated that a deeper recess may be able to increase the QE two to four times at deep UV wavelengths. The optical and electrical constants were taken from [6], where the electron diffusion length L_e was reported as 7 μm. The modeled results obtained a much closer fit to the experimental results when an effective electron diffusion length of 0.08 μm was used. We attribute this shorter effective diffusion length to surface band-bending. This effect has been discussed in [12] and [13].

Due to the low UV QE (~5%) in the recessed window devices, a Schottky device was studied [14]. The QE of the Schottky device, shown in Fig. 3, demonstrated almost 15% QE below 350 nm, a flat peak response of ~16% from 362 to 425 nm, and cut off wavelength of 450 nm. This improved QE in the UV range was attributed to the semitransparent contact spreading the electric field across the device mesa, allowing more efficient collection of higher energy photons [10]. Devices fabricated from the same wafer without using the semi-transparent contact exhibited QE characteristics nearly identical to the standard APD.

V. Noise

The excess noise of an APD originates from the statistical nature of impact ionization events. The ratio of ionization coefficients for electrons and holes α and β, respectively, strongly influence the excess noise factor F. The ratio $k = \beta/\alpha$ should be minimized for electron-initiated gain and maximized for hole-initiated gain. The equation governing this behavior is

$$F_n = M_n \left[1 - (1-k) \left(\frac{(M_n - 1)}{M_n} \right)^2 \right] \tag{1}$$

for electron-initiated gain, where M_n is the electron multiplication factor [15].

The excess noise factor $F(M)$ of the standard GaP devices was measured using an HP8970B noise figure meter with a standard noise source and an Argon laser (351, 363 nm). Using (1) yielded an effective k value of 0.4 for the standard GaP APDs, as shown in Fig. 4. Bulk GaP has been reported to have equal

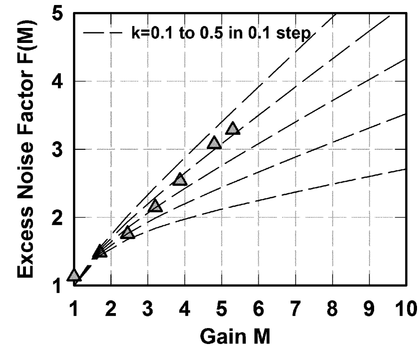


Fig. 4. Excess noise factor versus gain for the standard GaP APD: UV(351, 363 nm), RT.

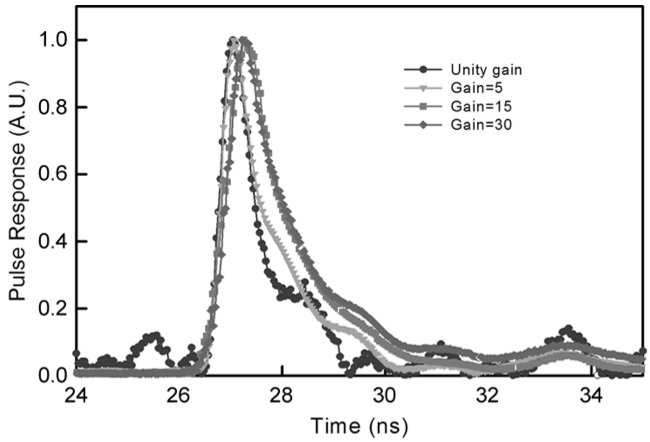
ionization coefficients for holes and electrons, which yields an effective k value of 1 [6]. The much lower excess noise achieved in the GaP APDs was attributed to the short UV absorption length, which resulted in single-carrier injection at the measurement wavelength. This was confirmed by examining the power absorption at 363 nm, according to $P_d/P_O = e^{-\alpha d}$, where P_d is the power at a depth of d in the device P_O is the incident power, and α is the absorption coefficient obtained from [6]. $P_d/P_O = 1.8 * 10^{-3}$ and $3.4 * 10^{-6}$ at the p-i and i-n interfaces, respectively. Additionally, the dead length effect in these devices played a much more significant role in the short i-region than in bulk material. This dead length effect reduced the high-gain tail of the gain distribution, thus reducing the excess noise [16].

VI. Speed

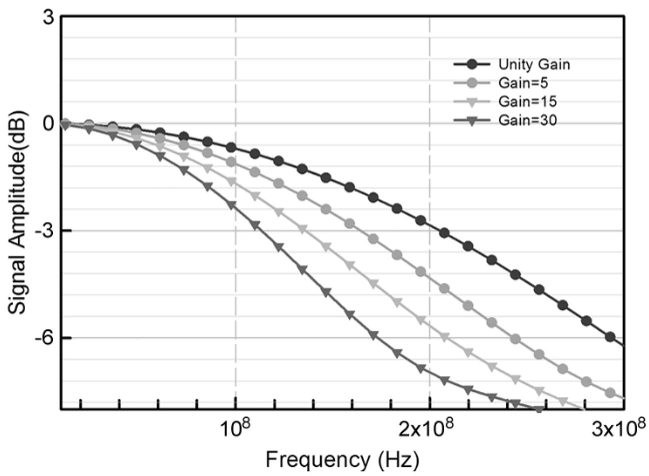
The normalized pulse response data of the standard GaP APD, shown in Fig. 5(a), indicated that the device speed was *RC* limited, as evidenced by the exponential tail. The speed response was taken using a 266-nm Nd:YAG laser with a 500-ps pulsewidth and a 7.5-kHz period. The device speed was measured at unity gain, as well as at gains of 5, 15, and 30. The gain was determined from the dc response and confirmed to match the gain acquired from ac response, which is obtained from the fast Fourier transform (FFT) from the response pulse. A device capacitance of 12.25 pF resulted from a 240-μm diameter GaP APD, which agreed well with the calculated capacitance of 12.2 pF. The device measured was larger than desirable for speed measurements, due to the constraints of the probe geometry, which had a large pitch. The large capacitance thus contributed to an *RC* limitation of ~250 MHz, as seen in Fig. 5(b). Taking the Fast-Fourier Transform (FFT) of the time response, shown in Fig. 5(b), resulted in a frequency of $f_{3\,\mathrm{dB}}$ ~210 MHz, at unity gain. The bandwidth slowly decreases with gain, reaching a 110 MHz at a gain of 30, thus at high gains, the device become transit time limited.

VII. Conclusion

GaP APDs, with thin device layers have been processed, utilizing both a p-i-n and recessed window p-i-n structure, as well as a Schottky structure. The results showed low dark currents, good QE, and high gains up to 10^3, with good uniformity across



(a)



(b)

Fig. 5. (a) Normalized time domain speed response. (b) Bandwidth of GaP APDs.

the wafer. The peak QE at 440 nm indicated Γ-valley absorption, rather than band-edge absorption. The recess window device structure confirmed the enhancement of UV detection via reduction of the p-layer thickness. Additionally, the Schottky structure demonstrated potential for enhanced UV detection, by employing a thin semitransparent contact.

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Dr. Woodall was elected an IBM Fellow in 1985, by five major IBM Research Division Awards, 30 IBM Invention Achievement Awards, and a Dollar 80,000 IBM Corporate Award in 1992 for the invention of the GaAlAs/GaAs heterojunction. He has nine NASA certificates of recognition, a 1975 IR-100 Award, 1980 Electronics Division Award of the Electrochemical Society (ECS), 1984 IEEE Jack A. Morton Award, 1985 ECS Solid State Science and Technology Award, 1988 Heinrich Welker Gold Medal and International GaAs Symposium Award, 1990 American Vacuum Society (AVS) Medard Welch (Founder's) Award, its highest honor, 1997 Eta Kappa Nu Vladimir Karapetoff Eminent Members' Award, 1998 American Society for Engineering Education's General Electric Senior Research Award, 1998 Electrochemical Society's Edward Goodrich Acheson (Founder's) Award, its highest honor, IEEE Third Millennium Medal (2000), and the Federation of Materials Societies' 2002 National Materials Advancement Award. He was elected to the National Academy of Engineering in 1989, and as a Fellow of the American Physical Society in 1982, ECS Fellow in 1992, and AVS Fellow in 1994. His national professional society activities include President of the ECS (1990 and President of the AVS (1998–1999). Most recently, President Bush awarded him the 2001 National Medal of Technology.