Optical Receiver Operation With High Internal Gain of GaP and GaAsP/GaP Light-emitting diodes

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ABSTRACT

Light-emitting diodes from a RGB lamp have been operated as optical receivers under various reverse bias voltage conditions. For the green emitting GaP based LED's and the red emitting GaAsP based LED's for values of the applied reverse bias voltage near avalanche breakdown internal photocurrent gain has been found with values exceeding 10000 for low light intensities. The photoresponse time has been measured to be in the microsecond range, limited basically by the RC time constant.

Keywords: Light-emitting diode, GaP, GaAsP, photodiode, avalanche multiplication, gain,

1. INTRODUCTION

There have been various proposals to use optical emitters as photoreceivers for applications in half-duplex optical links. A 1300nm InGaAsP Fabry-Perot laser has been operated as photodetector with a cutoff frequency of 600MHz[1], Quantum cascade lasers have been used to detect far-infrared light[2] and vertical cavity surface emitting lasers (VCSEL's) have been used as resonant cavity enhanced photodetectors[3,4]. In the latter case also photocurrent gain exceeding 10 based on the avalanche mechanism has been observed. As an example for another non-classical application of LED's for electro-optical measurements, it can be mentioned that AlGaAs light-emitting diodes (LED's) have been used as sensitive measurement devices for femtosecond laser pulse characterization, using an autocorrelation technique[5]. Here we demonstrate the possibility to utilize low cost light-emitting diodes as fast and highly sensititive photodetectors.

2. EXPERIMENTAL

2.1 Measurement Setup

LED current-voltage (I-V) characteristics have been measured using a Keithley Model "2400" source measurement unit (SMU) in forward and a Keithley Model "487" high voltage SMU in reverse direction. The optical emission spectra have been measured using a PC based Ocean Optics type "PC2000" spectrometer and the reponsivity of the LED's have been measured without applied bias voltage, using a xenon lamp in combination with a "CM110" monochromator from CVI as optical source and a calibrated Hamamatsu "S2386-44K" silicon photodiode as reference. For the determination of the photoresponse time of the RGB LED's a green GaP LED with the same emission spectrum as the green LED in the RGB-device with a peak wavelength of 565nm has been modulated by a Melles-Griot "DLD103" laser controller in pulsed mode. In this case the bias voltage has been applied using the above mentioned Keithley "487" SMU and the photocurrent transients have been picked up using a American Laser System "Model 711" wideband current probe.

1.1 Sample description

The investigated LED's are 10mm Full Color RGB Lamps from Kingbright (Type "LF819") [6] with two blue emitting InGaN/GaN diodes on SiC substrate, a green emitting GaP based diode and a red emitting GaAsP on GaP diode.

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3. RESULTS AND DISCUSSION

1.1 Electro-optical characterization of the RGB light-emitting diodes

In the case of the blue LED with InGaN active layer we did not observe multiplication of photo induced charge carriers, because of premature reverse bias breakdown and relatively high reverse bias currents below breakdown. The green LED with an GaP active layer and the red LED with an GaAsP active layer, however, exhibited very low room temperature reverse bias currents (<10pA) below breakdown. Typical breakdown voltages were 130V in the case of the GaP LED with the peak emission wavelength of 565nm and 240V in the case of the GaAsP/GaP with the peak emission wavelength of 630nm. In Fig.1 we see the forward bias characteristics and in Table 1 additionally some other characteristic parameters of the GaP and GaAsP LED's, as the diode ideality factor, the saturation current, the junction capacitance for a reverse bias voltage of 10V and the diode series resistance.

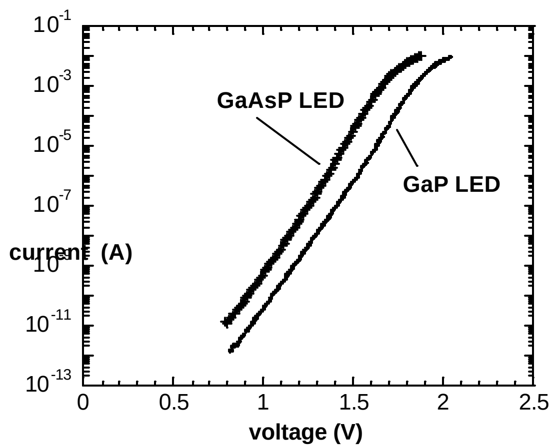

Figure 1: Room temperature forward bias current – voltage characteristics of the GaP and GaAsP LED's

LED type	Active layer material	Series resistance (W)	Ideality factor	Saturation current (A)	Junction capacitance at -10V (pf)	Typical reverse bias breakdown voltage (V)	Peak emission wavelength (nm)
Red	GaAsP	19.3	1.68	1.16e-20	2.5	240	630
Green	GaP	19.4	1.77	1.42e-21	4.7	140	565

Table 1: Electrical and optical device parameters of the red and green LED types within the RGB lamp

In Figure 2 the optical emission spectrum and the wavelength dependence of the relative responsivities when operated as photoreceivers of the GaP and the GaAsP LED's are shown. The green GaP LED has a peak emission wavelength of 565nm and is can be operated as photodiode in the wavelength range between 450nm and 570nm. A pronounced exciton related absorption peak around 550nm can be observed. In the case of the red GaAsP LED the emission maximum is at 630nm and the device can be operated as receiver at wavelengths between 500nm and 650nm with a maximum in the responsivity at 600nm. For both LED's there is a sufficient overlap between the optical emission and absorption spectrum so that the LED's can be used for a optical bidirectional communication link, using the same type of LED as well as emitter and receiver. A drawback is of course the need for an additional high voltage power supply.

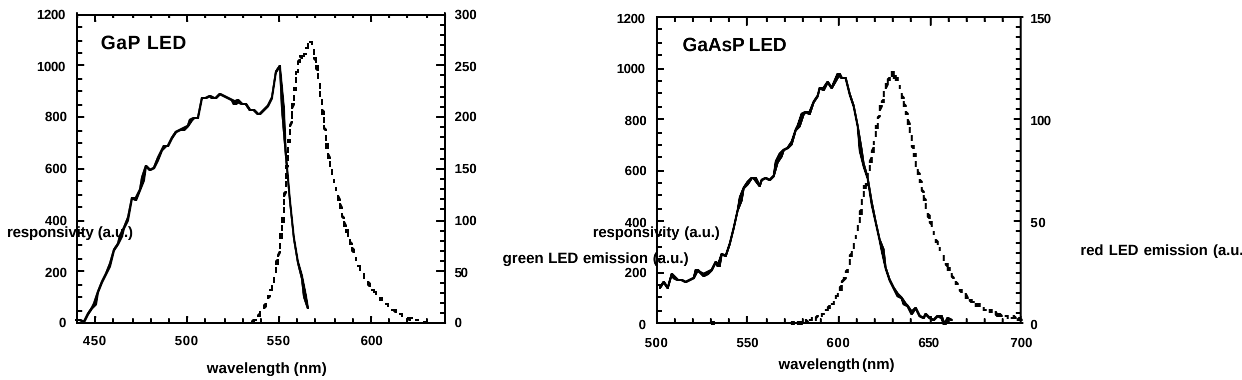

Figure 2: Responsivity (full line) and optical emission (dotted line) spectra of GaP and GaAsP LED's

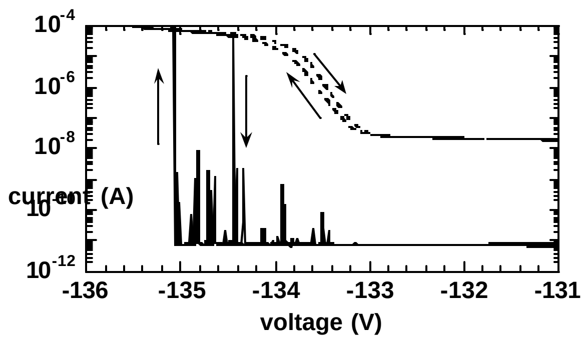

Figure 3: Dark current (full line) - and photocurrent (broken line) – voltage characteristics near reverse bias breakdown of a GaP LED measured for increasing and decreasing applied voltage ramps (as indicated by the arrows)

In Fig. 3 the current-voltage characteristics of the green GaP LED is shown for elevated values of the bias voltage between -131V and -136V with and without illumination. Reverse bias breakdown is observed in this voltage range. Measuring the device current during increasing and decreasing voltage ramps, we observe a wide open hysteresis in the dark current-voltage characteristics. This can not be due to device heating, because we measured that the breakdown voltage for these diodes increases with increasing temperature, as expected in the case of avalanche multiplication related device breakdown. A possible explanation for the hysteresis in the dark I-V characteristics is charge trapping and a modification of the local electric field due to the trapped charge. Illuminating the LED with green or blue light with emission peak wavelengths of 470nm and 565nm respectively, a photocurrent that is only slightly increasing with increasing reverse bias voltages has been measured. Near device breakdown the photocurrent increases strongly in a voltage range, where we do not yet observe the inset of dark current reverse bias breakdown. This is as an example plotted in Figure 3 for the case of the LED illumination with green monochromatic light, that induces a primary photocurrent of 3.3nA. At -131V we measure a photocurrent of about 20nA. Increasing the bias voltage further, we observe a large increase in the total LED current for applied voltages between -133V and -134.5V. In this voltage range, the dark current can still be neglected, but above -133.5V reverse bias voltage, a substantial increase of the dark current noise is found.

Now we define the photo induced current, as measured under short circuit conditions, as the primary photocurrent and the ratio between the photocurrent at higher applied reverse bias voltages and this primary photocurrent as the internal gain of the LED, that has been used as receiver.

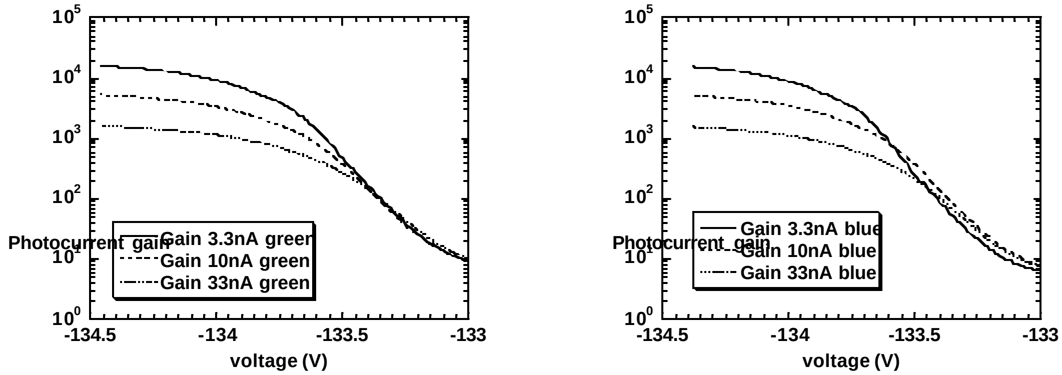

Figure 4: Photocurrent gain as a function of the bias voltage slightly below breakdown of a GaP LED illuminated with blue and green light with for three different light intensities (only increasing applied reverse bias voltage ramps)

In Fig.4 the above defined photocurrent gain has been plotted in the voltage range between -133V and -134.5V, illuminating the GaP LED with green or blue light with different intensities, corresponding to primary photocurrents of 3.3nA, 10nA and 33nA respectively. We observe in all cases a strong monotonic increase of the gain with increasing reverse bias voltages. At about -133.5V a photo gain of 200 is achieved, almost independent of the incident light intensity and excitation wavelength. For further increasing values of the reverse bias voltage, the gain increase is more prominent for low light intensities. At -134V gain values of 10000 for low light intensities (primary photocurrent of 3.3nA) and of 1000 for higher light intensities (primary photocurrent of 33nA) have been measured.
Large values of photocurrent gain have been observed in a large variety of photoreceivers. In most cases, however, there is a tradeoff between gain and response time[7].

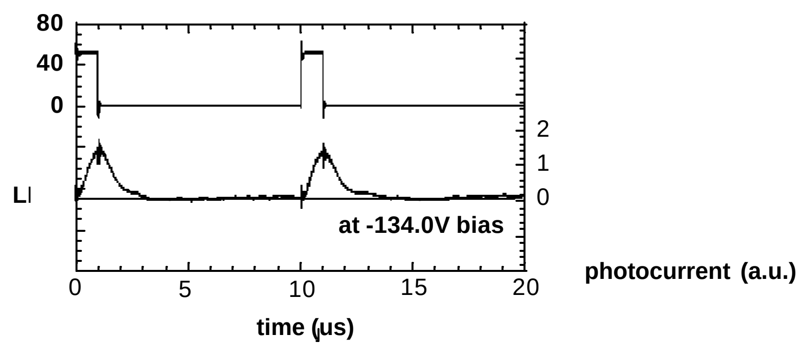

Figure 5: Photocurrent response (lower trace) of a GaP LED measured after illumination with 565nm light pulses of a second GaP LED. The LED current of the emitter is shown in the upper trace.

In order to test the response time of the GaP LED as photoreceiver, we illuminated it with a second pulsed LED and measured the resulting photocurrent using a wideband inductive current probe with preamplifier. The oscilloscope traces of the 1µs long modulating current pulses with 60mA amplitude of the LED used for excitation and of the resulting photocurrent transients measured in the receiving GaP LED with an applied bias voltage of -134V are shown in Fig. 5. It can clearly be seen that rise and fall times are in the microsecond range. The capacitance values with applied reverse bias voltages exceeding 10V(see table 1) are also sufficiently low, so that the R C time constant allows for microsecond response times.

It should be noted that very similar behavior with large photocurrent gain values near reverse bias breakdown has also been observed for the red GaAsP based LED used as photoreceiver, when illuminated with the green LED. As seen earlier in Fig. 2, this type of LED is not sensitive in the blue spectral range. An application of the complete RGB lamp in a frequency selective bidirecional emitter/receiver module should be possible. The blue light is received only by the green and the blue LED – in the latter case, however, without photogain. The red light is received only by the red LED and the green light is received by the red and the green LED.

4. CONCLUSIONS

GaP and GaAsP light-emitting diodes have been demonstrated to be suitable as sensitive and fast photoreceivers, operating them near reverse bias breakdown. Very high internal gain values exceeding 10000 for low light intensities have been determined.

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