Ultrafast Transport Dynamics of p-i-n Photodetectors Under High-Power Illumination

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***Abstract*— We studied ultrafast transport dynamics of high-speed p-i-n photodetectors under high illumination using an electrooptic sampling technique. Under high illumination, saturation nonlinearities were found to be dominated by a space-charge-screening effect. A transient forward external current was also observed, which was attributed to an underdamped plasma oscillation. The external bias required to compensate these nonlinear effects increased with increased illumination.**

***Index Terms*— InGaAs, p-i-n photodetector, transport, ultrafast.**

THE DEVELOPMENT of high-speed and high-sensitivity photodetectors operating at 1.3–1.55-μm wavelengths is fundamental for new high-bit-rate long-wavelength optical communication systems. Surface normal p-i-n photodetectors have demonstrated bandwidth in excess of 100 GHz [1], [2]. In general, the thickness of the absorbing layer in a surface-normal p-i-n photodiode has to be reduced for ultrahigh-speed response at the expense of detection efficiency. Furthermore, the device active area has to be reduced in order to reduce the photodiode *RC* time constant [1], [2]. A small active area diameter results in higher carrier concentrations for a given power level. Implementation of optical preamplifier or heterodyne detection in communication systems significantly increases the optical power incident on photodetectors [3]. These new developments stimulate great interest [4]–[6] in the study of high field and high illumination transport nonlinearity in ultrawide-band long-wavelength photodetectors on 100-fs to 10-ps time scale.

Heterodyne techniques have been used to characterize the magnitude of the nonlinear frequency response of p-i-n photodetectors under high illumination [6]. Pump-probe absorption and electroabsorption (EA) measurements [7]–[11] have also been performed to investigate the carrier dynamics under high field. On the other hand, electrooptical (EO) sampling provides a unique time-domain technique to investigate the transport dynamics by exciting the carriers in the absorption layer while probing the electrooptical property changes induced by the external current flow [2], [12], which is directly related to the charge motion in the depletion layer. In this letter, we present a study of high power characteristics of long-wavelength ultrawide-band surface-normal p-i-n photodetectors using an EO sampling technique.

We have fabricated 120-GHz bandwidth back-illuminated InGaAs–InP p-i-n photodetectors which reduced the RC time constant of the diode by an undercut geometry and minimized the parasitic capacitance by using an air-bridged metal waveguide [10]. The intrinsic absorption layer thickness was 180 nm with a diameter of 2 μm. The detector impulse current response was measured by EO sampling using the InP substrate as an electrooptic modulator. The InP substrate was thinned down to a thickness of 100 μm before measurements. A 100-MHz Ti-sapphire laser delivering 200-fs pulses at a wavelength of 0.98 μm was used as the measurement source. The excitation and EO probe beams were focused through the back side of the wafer. The device was contacted by microwave probes of 50-Ω characteristic impedance and biased through a 40-GHz external bias tee.

Fig. 1 shows the measured bias-dependent EO signals with 13-fC photogenerated charge in the absorbing intrinsic region per excitation pulse, corresponding to an initial generated carrier density of $1.5 \times 10^{17}/\text{cm}^3$. At -1-V reverse bias, the measured response had a pulsewidth of 3.3-ps full-width at half-maximum (FWHM) and a significant tail. The integrated signal was weaker than the signal at higher reverse bias, indicating a p-i-n junction that was not fully depleted. At -2-V bias, the response reached a minimum pulsewidth of 2.7 ps FWHM. The signal magnitude was totally recovered, indicating a fully depleted p-i-n junction. The broader pulsewidth and the slow tail at -1-V bias was attributed to carrier trapping at heterojunctions and a large junction capacitance due to a not-fully depleted intrinsic region [2]. For reverse bias higher than or equal to -2 V, the junction capacitance was reduced due to an increased depletion width. The heterojunction barrier heights were also reduced due to higher bias, so that the carrier trapping time was much shorter than carrier transit time and could thus be neglected [2]. While bias increased from -3 to -5 V, the response got longer from 2.8 to 3.3 ps. This was due to increased depletion widths in the p-doped and n-doped regions, which resulted in increased transit time. The negative responses observed at 10 ps time delay were echo signals induced by the impedance mismatch at the microwave probe contact.

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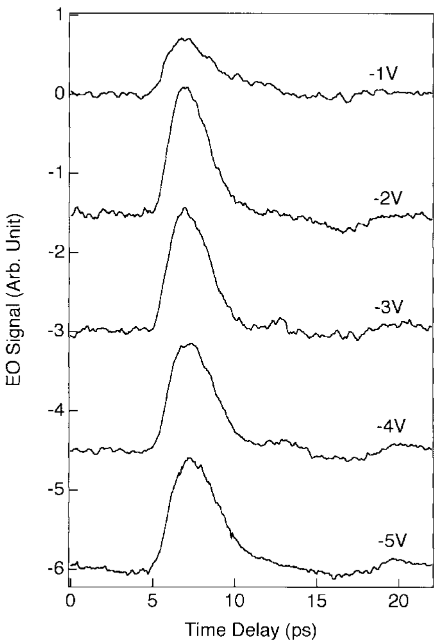

Fig. 1. Bias dependent responses with 13-fC photogenerated carriers in the intrinsic region. Data are vertically displaced for clarity.

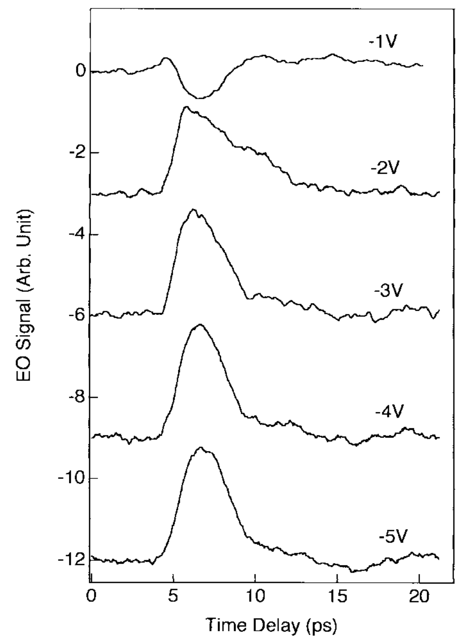

Fig. 2. Bias dependent responses with 29-fC photogenerated carriers in the intrinsic region. Data are vertically displaced for clarity.

Fig. 2 shows the measured bias dependent responses under higher illumination. The photogenerated charge induced by each excitation pulse was 29 fC, corresponding to a generated carrier density of $3.2 \times 10^{17}/\text{cm}^3$. While the impulse responses at reverse bias higher than −3 V showed similar behaviors to the corresponding responses in Fig. 1, the impulse responses at lower bias showed dramatically different behaviors. With a bias of −1 V, the observed signal first went positive, then became negative within 1 ps. This negative transient current was recovered in 5 ps. After 5 ps, the current was back to positive with a relatively long decay time. When we increased the bias to −2 V, this negative-transient behavior disappeared. Instead, a saturated slow response with a pulsewidth of 4.9 ps was observed. Similar slow responses were previously observed in GaAs based traveling wave and surface normal p-i-n photodetectors under high illumination [14]. This slow response was recovered to a pulsewidth of 3.4 ps when we increased the reverse bias to −3 V.

We found that the bias required to compensate the observed negative transients and the slow saturated positive responses increased monotonously with increased excitation intensities. Fig. 3 shows the measured bias dependent response under even higher illumination. The photogenerated charge induced by each excitation pulse was 68 fC, corresponding to a generated carrier density of $7.6 \times 10^{17}/\text{cm}^3$. The negative transient was observed with reverse-bias voltages lower than −4 V. With increased bias, the amplitude of the positive component increased while the response at long delay time decayed faster. The width of the negative transient showed weak dependence on the bias voltage. It was interesting to notice that the turn-on delay for the negative transient increased from less than 1 ps to ∼1 ps with increased bias. With −5 V bias, the negative transient disappeared and the EO signal showed the slow saturated positive response with a FWHM of 7.2 ps.

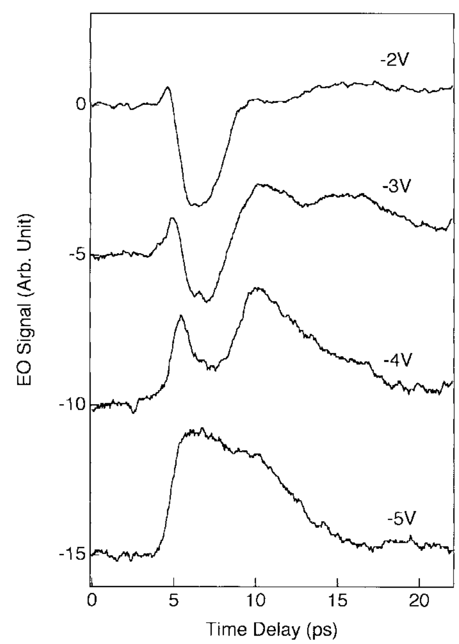

Fig. 3. Bias dependent responses with 68 fC photogenerated carriers in the intrinsic region. Data are vertically displaced for clarity.

The monotonous correspondence between the generated carrier density and the required external compensation field suggested that the observed behavior might be induced by the collapse of the electric field due to space charge screening effects. This agreed with the previous heterodyne experiments of a p-i-n photodetector [6] and previous absorption studies of a horizontal MQW p-i-n photoconductive gap [8] and a p-i-n saturable absorber [10], which showed the collapse of the electric field on the time scale of a picosecond or less than a picosecond under high field and high illumination with a two-dimensional (2-D) carrier density on the order of $10^{11}/\text{cm}^2$.

Our data are consistent with the following simple scenario. When electrons and holes generated in the intrinsic region drifted in opposite directions, they generated a space charge field to screen the built-in and biased electric fields. Under low illumination, the generated maximum screening field was much smaller than the biased and build-in fields and this effect can be neglected. When the illumination was increased, the induced space-charge-field was also increased until it was comparable to the built-in and bias dc electric field, which screened the biased electrical field and saturated the device. Under a screened electric field, carriers traveled at a slower drift velocity and a slower positive response was expected (-5 V trace in Fig. 3 and -2 V trace in Fig. 2). With a higher bias, the illumination required to saturate the photodetector increased. Under fixed illumination, this screening effect could thus be compensated by applying a higher external bias.

Under even stronger illumination or with lower bias, a negative current transient was observed. The turn-on delay of the negative transient effect depended on the generated carrier density and pre-existing dc field which determined the time and distance carriers had to travel in opposite direction in order to build up a screening field that was comparable to the pre-existing dc electric field. With fixed illumination, the turn-on delay would increase with higher external bias. This agreed with our observation shown in Fig. 3. When the space charge field canceled the bias and built-in field, the drift velocity did not instantaneously decrease to zero but required several scattering times, consequently the electron and holes would keep drifting. This might set up a space charge field greater than the pre-existing dc field and could be responsible for the negative transient current observed in our devices. At longer time delays, a long positive tail was observed under a lower bias and high illumination. This might be attributed to the drift velocities under a screened electric field.

In summary, we have studied the ultrafast transport dynamics of ultrawide-band long-wavelength surface-normal photodetectors under high illumination using an electrooptic sampling technique. A photodetector structure was fabricated using an undercut mesa and air-bridge coplanar waveguide to reduce the diode resistance and parasitic capacitance. Under low illumination, the detectors had transit-time-limited responses which were governed by the carrier velocity, depletion width, and carrier trapping at heterojunction barriers. Under high illumination, a strong space-charge-screening effect was observed. This screening effect slowed down carrier velocities and broadened impulse responses. A transient negative current was also observed. The reverse bias required to compensate the space charge effects increased with increased illumination.

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