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Quantum Efficiency of InP/InGaAs Uni-Traveling-Carrier Photodiodes at 1.55-1.7 um Measured Using Supercontinuum Generation in Optical Fiber

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1. Introduction

Uni-Traveling-Carrier Photodiodes (UTC-PDs) [1] are promising candidates as the ultrafast optical-to-electrical signal converters in large-capacity fiber optic communication systems [2, 3] and ultrafast measurement systems [4, 5], because of their high-speed and high-current-density operation. In order to apply UTC-PDs in future bandwidth-weighted transmission schemes, in which the zero-dispersion and none zero-dispersion wavelength regions of the optical fiber are respectively used for ultra-high-speed and intermediate-speed transmissions [6], it is important to clarify their absorption characteristics in a wide wavelength range around 1.55 μm. However, so far, little is known about the optical absorption properties of the p-InGaAs that acts the photo-absorption layer in UTC-PDs [7, 8].

In this paper, we present a systematic study of the external quantum efficiency (η) of UTC-PDs with the acceptor doping density in the photo-absorption layer (N_a) ranging from 2.5 x 10^{17} to 2.5 x 10^{18} cm^{-3}. For the efficiency measurement, a supercontinuum (SC) generated in the optical fiber [9] was used as a monochromatic optical source. The high power density and spatial coherency of the SC enables us to derive η with the high spectral and spatial resolution. The observed flatness of η at wavelength from 1.5 to 1.6 μm shows the applicability of UTC-PDs to wide bandwidth transmission systems. Furthermore, it is found that the UTC-PD with N_a = 2.5 x 10^{18} cm^{-3} has higher external quantum efficiency than those with lower N_a at wavelengths around 1.7 μm. This suggests the extensive bandgap shrinkage when N_a reaches mid 10^{18} cm^{-3}.

2. Experiments

The three UTC-PD structures studied in this paper have a 210-nm $In_{0.53}Ga_{0.47}As$ photo-absorption layer with N_a of 2.5 x 10^{17}, 1.0 x 10^{18}, and 2.5 x 10^{18} cm^{-3}, respectively. Details of the structures are presented in reference [10]. The active area of the devices is 100 x 100 μm^2.

Figure 1 is a schematic diagram of the setup for the

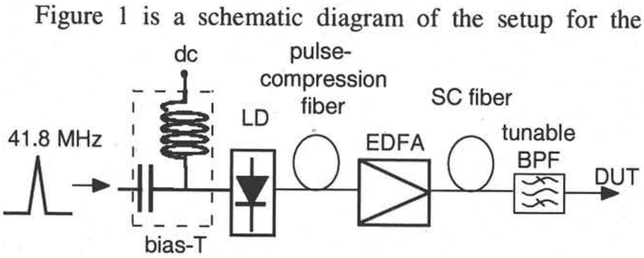

Fig. 1: Schematic diagram of the monochromatic optical source.

monochromatic optical source. A pump pulse train with the wavelength of 1.55 μm produced from a gain-switched LD passed through a pulse-compression fiber with a normal dispersion and an Erbium doped fiber amplifier and was fed into a 0.5-km dispersion-shifted fiber (SC fiber). Due to the nonlinear effect in this fiber, the spectrum of the pulse train spread from 1.35 to more than 1.75 μm; that is, SC was generated. Using a tunable band-pass filter (BPF), a monochromatic pulse train with wavelength from 1.550 to 1.725

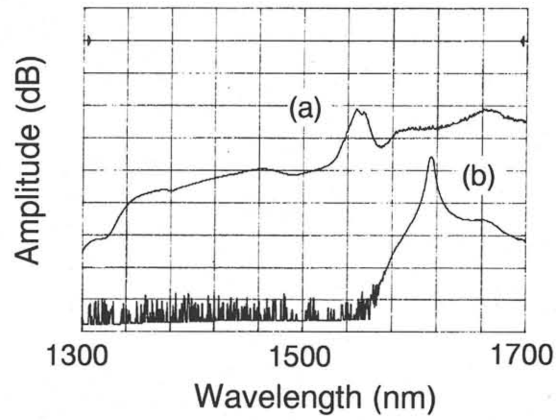

Fig. 2: Typical spectra of the monochromatic optical source. (a) and (b) were measured before and after a tunable band-pass filter (λ_c = 1.615 μm), respectively.

μm was cut out from this SC. Figure 2 shows the typical spectrum of the optical pulse before and after the BPF. The spectral width of the monochromatic pulse (Δλ) was 3 nm when the center wavelength (λ_c) was from 1.550 to 1.685 μm, and Δλ was 30 nm when λ_c was 1.725 μm. The monochromatic pulse was illuminated to UTC-PDs, and η at each wavelength was obtained from the relation between the input optical power and observed photocurrent. The SC source for photodiode responsivity measurement has two characteristic features not found in conventional monochromatic optical sources consisting of lamp and monochromator: (1) high power that provides both high spectral resolution and a high signal-to-noise ratio in the measurement; and (2) spatial coherency that enables us to focus beam into the small area, which results in the elimination of error due to the spatial fluctuation of layer thickness.

3. Results and Discussion

Figure 3 shows the relations between the measured photocurrent and input optical power at four different λ_c. Here, N_a = 2.5 x 10^{17} cm^{-3} and the applied dc bias was -0.5 V. At each λ_c, the measured photocurrent was exactly proportional to the input optical power. This reflects that a monochromatic beam can be extracted with sufficient power from the SC source, even when the bandpass is as little as 3-nm wide.

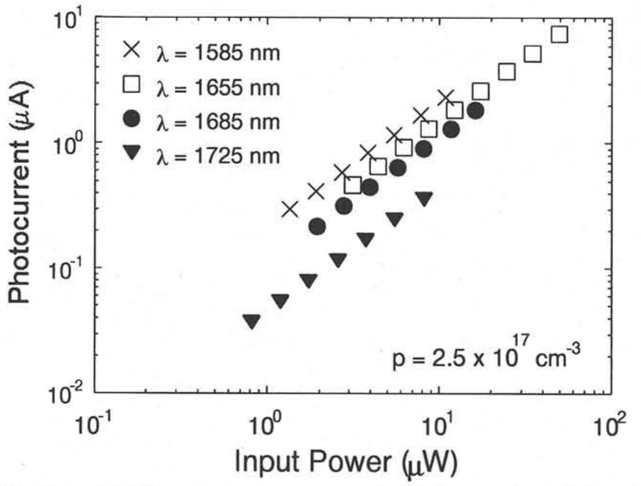

Fig. 3: Relations between measured photocurrent and input optical power at four wavelengths.

From the data shown in Fig. 3, η was derived. The results are plotted as a function of λ_c in Fig. 4. In this figure, the result for the device with N_a of 1.0 and 2.5 x 10^{18} cm^{-3} is also plotted, and data between 1.445 and 1.525 μm were obtained using a tunable laser source. When λ_c was shorter than 1.6 μm, η was around 23 % and almost completely independent of λ_c and N_a. The obtained flatness region covers the gain bandwidth of a recently developed wideband fiber amplifier [11]. This result indicates that UTC-PDs can be applied to future high-density transmission systems in which the bandwidth of the optical fiber and amplifier is fully utilized.

When λ_c is longer than 1.6 μm, η gradually decreases as λ_c increases. This is quite reasonable because the energy gap of undoped InGaAs is around 0.75 eV (λ = 1.65 μm). An interesting point here is that the decrease in η when N_a = 2.5 x 10^{18} cm^{-3} at around 1.7 μm is much smaller than that when N_a is 1.0 x 10^{18} cm^{-3} or less. The ratios of the state density occupied by electrons against the total state density at the valence band edge in InGaAs are estimated to be 95, 88, and 73 % for N_a = 2.5 x 10^{17}, 1.0 x 10^{18}, and 2.5 x 10^{18} cm^{-3}, respectively, at room temperature. This numerical assessment means η at around 1.7 μm decreases slightly with N_a if the bandgap is independent of N_a. The experimental result completely opposite to this assessment suggests that there is extensive bandgap shrinkage in p-InGaAs when N_a become closer to mid 10^{18} cm^{-3}.

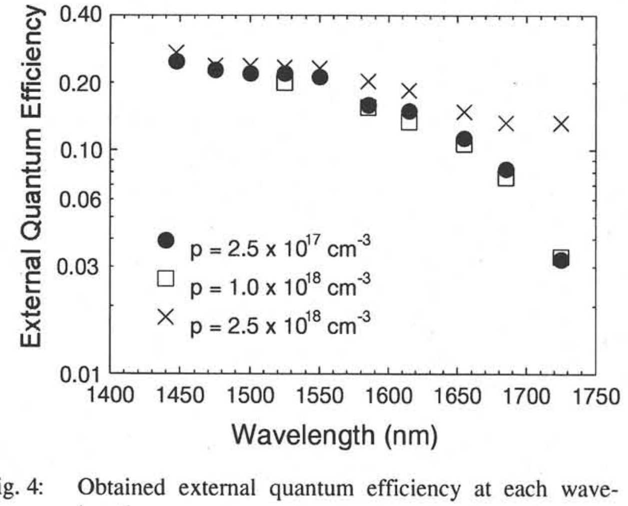

Fig. 4: Obtained external quantum efficiency at each wavelength.

4. Conclusion

We have systematically studied quantum efficiency of the UTC-PDs with the acceptor doping density in the photo-absorption layer from 2.5 x 10^{17} to 2.5 x 10^{18} cm^{-3} using supercontinuum generated in optical fiber as the monochromatic optical source. The observed flatness of η in the wavelength from 1.5 to 1.6 μm shows the applicability of UTC-PDs to wide bandwidth transmission systems. Furthermore, the UTC-PD with N_a = 2.5 x 10^{18} cm^{-3} has a larger external quantum efficiency than those with lower N_a at the wavelength around 1.7 μm. This result suggests that intense bandgap shrinkage occurs when N_a reaches mid 10^{18} cm^{-3} in p-InGaAs.

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