Abnormal photocurrent–voltage behavior of GaAs/AlGaAs multiple shallow quantum well \( p-i-n \) diodes

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We have observed the abnormal photocurrent–voltage (\( I-V \)) behavior in GaAs/AlGaAs multiple shallow quantum wells \( p-i-n \) diodes. Under the illumination of a laser, two current plateaus were developed at the negative conductance region of the \( I-V \) curve, along with some hystereses depending on the scan direction. At the first plateau, two major oscillations of \( \sim 120 \) kHz and \( \sim 37 \) MHz were observed with several minor oscillations of frequencies below the latter, while this latter component was uniquely at the other plateau. Analyzing the electrical and the optical oscillations, we explain that one hysteresis at the first plateau was due to the low frequency bias-circuit oscillations, whereas the other at the next plateau was attributed to the intrinsic behavior of the \( p-i-n \) diode. © 1998 American Institute of Physics. [S0003-6951(98)03620-1]

In the past several years, the negative differential conductance (NDC) of resonant tunneling diodes (RTDs) and of multiple quantum wells (MQWs) \( p-i-n \) diodes has been widely studied because of their applications to microwave devices\(^1\) and optical bistable devices\(^2,3\) respectively. The NDC of RTDs results from the resonant tunneling phenomenon, whereas that of MQW \( p-i-n \) diodes is due mainly to the electroabsorption change in MQWs and is dependent on both the wavelength and the intensity of the laser. The photocurrent–voltage (\( I-V \)) curves of RTDs often showed the current plateau with some hysteresis in the NDC region. This phenomenon has been studied extensively with interest in the fundamental physics and the possible applications of RTDs,\(^5\) and was attributed to electrostatic feedback effects by the charge build-up in the quantum well or to the electrical oscillations in the diode circuit. In this letter, we report our observations of abnormal \( I-V \) oscillations along with some hystereses in GaAs/AlGaAs multiple shallow quantum wells (MSQWs) \( p-i-n \) diodes under the illumination of high power laser.

The diode structures used in this study were grown by gas-source molecular beam epitaxy. Quarter-wavelength reflector stacks consisting of 14.5 pairs of 72.5-nm-wide AlAs/61.6-nm-wide Al\(_{0.05}\)Ga\(_{0.95}\)As were grown on a semi-insulating GaAs substrate, and followed by \( p-i-n-i-p \) layers. For \( p \) and \( n \) doping, Al\(_{0.05}\)Ga\(_{0.95}\)As layers were doped with Be \((1 \times 10^{19} \text{ cm}^{-3})\) and Si \((5 \times 10^{18} \text{ cm}^{-3})\), respectively. In each intrinsic region, 40.5 pairs of 10-nm-wide GaAs/5-nm-wide Al\(_{0.05}\)Ga\(_{0.95}\)As MSQWs were sandwiched between 20-nm-wide undoped Al\(_{0.05}\)Ga\(_{0.95}\)As spacers. An anti-reflection coating was made on the top of the device. Finally, two \( p-i-n \) diodes in the \( p-i-n-i-p \) layer were connected in parallel.\(^4\)

For \( I-V \) measurements, the 858 nm line of a semiconductor laser with a Gaussian beam of \( \sim 10 \mu \text{m} \) diameter was illuminated on the diode at room temperature. The wavelength of the laser was around the transition energy of the heavy-hole exciton ground state of MSQWs. We used the HP4145B parameter analyzer for \( I-V \) measurements. The ac components of the electrical signals were extracted by a bias-T and monitored by using the rf spectrum analyzer and the oscilloscope. Optical oscillations of the reflected laser from the diode were measured simultaneously by the same oscilloscope.

When the laser power \((P_L)\) was below \( \sim 1 \) mW, the \( I-V \) curve of the diode showed a photocurrent peak at the forward bias of about \( -0.5 \) V and the continuous NDC for higher reverse bias voltages. As the laser power was increased, the NDC was enhanced and eventually gave rise to two current plateaus, A and B, along with some hystereses, depending on the scan direction, as shown in Fig. 1(a) for \( P_L = 25 \) mW. The position of the photocurrent peak and of the current steps shifted to the higher reverse bias voltages, and both the plateaus and the hysteresis became wider. These results can be understood by the fact that the electric potential on the \( p-i-n \) diode was screened by the photogenerated carriers accumulated in the quantum wells and at both edges of the intrinsic layer. For the higher \( P_L \), the higher reverse bias voltage was needed to make the same potential in the intrinsic region of MSQW. Figure 1(b) shows the \( I-V \) curves of the diode with a 100 nF capacitor in parallel at \( P_L = 25 \) mW. When the capacitor was connected in parallel to the \( p-i-n \) diode, the first current plateau A disappeared from Fig. 1(b). Similar results were obtained by using different capacitors such as of 10, 47, and 220 \( \mu \text{F} \).

The electrical and the optical oscillations at A are shown in the bottom and the top traces of Fig. 2(a), respectively. High frequency (HF) components of \( \sim 36.7 \) MHz are carried by the low frequency (LF) oscillations of \( \sim 120 \) kHz. On the other hand, an ac component of unique frequency

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$\sim 37.1$ MHz is alone at the next current plateau B in both the electrical and the optical oscillations, as shown in the bottom and the top traces of Fig. 2, respectively. These results are also confirmed with the frequency spectra of HF oscillations at A and B, as shown in Figs. 3(a) and 3(b), respectively. A large number of side peaks are revealed below its main frequency of $\sim 36.7$ MHz at A, whereas unique frequency of $\sim 37.1$ MHz dominated the oscillations at B.

On the other hand, the intensity of the reflectivity oscillations in Fig. 2 is the maximum at the highest electric field in the MSQW p-i-n diode because of low electroabsorption. The oscillations in the two traces show approximately the same phase. From Fig. 2(a), the amplitudes of both the optical and the HF electrical oscillations are quenched around the valley of the LF electrical oscillations. The HF oscillations were suppressed at the dc bias voltages below the left
edge of A. This result implies that the LF oscillation pushed the dc bias outside the NDC region in the forward direction. Therefore, the HF oscillations are associated with the intrinsic behavior of the p-i-n diode, whereas the hysteresis at A can be explained with the bias-circuit oscillations of the LF. The stability criteria at the bias circuits are dependent on parasitic R-L-C circuit elements as well as the intrinsic characteristics of the p-i-n diode. The frequency and amplitude of oscillations showed a slight dependence of the dc-bias voltage position at the plateaus. At A, the bias voltage applied on the p-i-n diode oscillated with the LF bias-circuit oscillations, and multiple side peaks of HF oscillations were revealed as shown in Fig. 3~a!. As the reverse bias voltage increased, the optical oscillations started to occur around the left edge (\( \sim 1 \) V) of A with the minimum value of reflectivity and disappeared at the right edge (\( \sim 3.5 \) V) of B with the maximum value of reflectivity, as shown at top traces in Fig. 2. From a comparison of the optical and the electrical oscillations, we found that the maximum amplitude of HF oscillations approximately covered the whole voltage spans of A and B.

The widths of two hystereses depended on the electrical parameters such as the resistance and the capacitance in the measurement circuit, indicating that the hysteresis was closely related with the electrical oscillations. Although the first hysteresis at A is clearly due to only LF electrical oscillations in the bias circuits, the second hysteresis at B may be partly due to the electrostatic feedback effect of accumulated carriers at the edge of the intrinsic layer in the p-i-n diode under the illumination of high laser power. The electrostatic feedback effect at a given external bias voltage in the NDC region leads to two photocurrent states depending on the scan direction. The second hysteresis can be attributed to the intrinsic properties of the MSQW p-i-n diode including both the electrostatic feedback effects of accumulated carriers and the HF electrical oscillations.

In summary, we observed the abnormal \( I-V \) characteristics of MSQW p-i-n diodes under the illumination of a high power laser. Two current-plateau regions were accompanied with some hystereses and oscillations. One hysteresis was due to LF bias-circuit oscillations, whereas the other was attributed to the intrinsic behavior of the MSQW p-i-n diode under the illumination of a high power laser. Oscillations in the reflected laser beam indicated that the maximum amplitude of voltage oscillations in the intrinsic region of MSQW p-i-n diode was approximately equal to the whole width of the current plateaux. We also observed the similar results from other single and stacked MSQW p-i-n diodes.

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