Optical and electrical tuning of the frequency in self-oscillating multiple shallow quantum-well diodes

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We have studied photoinduced self-oscillation characteristics in GaAs/AlGaAs multiple shallow quantum-well diodes as a function of bias voltage and laser power. Under the illumination of a laser of wavelength corresponding to the exciton absorption energy, the $I-V$ curve of the diode revealed a large negative differential conductance region where the electrical and optical oscillations were observed in the same phase. The oscillation frequency was widely tuned by either bias voltage or laser power, and this demonstrates a large potential of the device scheme for the electrical and optical signal generators with wide frequency tunability. © 1999 American Institute of Physics.

In the past several years, the negative differential conductance (NDC) of diode structures such as the resonant tunneling diode (RTD) and multiple quantum-well diode (MQWD) has been widely studied because of its practical applications and the academic interest in fundamental phenomena.1,2 In particular, MQWDs with photoinduced NDC characteristics have been applied to various advanced devices such as microwave oscillators,1,2 optical bistable devices,3,4 optical regenerators,3,5 etc. Recently, we have studied both the intrinsic and extrinsic behavior in photoinduced self-oscillations in multiple shallow quantum-well diodes (MSQWDs).6 Those oscillations were present at the NDC region of the $I-V$ curves where two current plateaus occurred along with some hystereses. The origin of similar phenomena observed in RTD structures has been controversial between the electrostatic feedback effect7 and the electrical oscillation effect.8 In this letter, we further explore the tuning characteristics of photoinduced self-oscillations in MSQWDs structures with respect to bias voltage and laser power.

The pin diode structures were grown for this study by gas-source molecular beam epitaxy. In order to enhance the optical absorption for the input laser,5 quarter-wavelength reflector stacks (QWRS) consisting of 14.5 pairs of 72.5-nm-wide AlAs/61.6-nm-wide Al0.1Ga0.9As, and a double pin structure was grown on a semi-insulating GaAs substrate. An antireflection coating was also made on the top of the device. For $p$ and $n$ doping, Al0.1Ga0.9As layers were doped with Be ($1 \times 10^{19} \text{ cm}^{-3}$) and Si ($5 \times 10^{18} \text{ cm}^{-3}$), respectively. In the intrinsic region of each pin structure, 20.5 pairs of 10-nm-wide GaAs/5-nm-wide Al0.05Ga0.95As MSQWs were sandwiched between 20-nm-wide undoped Al0.1Ga0.9As spacers. Two mesa structures were fabricated on the pinip diode. The area of the upper mesa was $40 \times 50 \mu\text{m}^2$, and that of the lower was $50 \times 75 \mu\text{m}^2$. Finally, two pin diodes were connected in parallel, as shown in the inset of Fig. 1.

For photocurrent–voltage measurements, the 856 nm line of a semiconductor laser with the Gaussian beam of $\sim 10 \mu\text{m}$ diam was illuminated on the diode at room temperature. The wavelength of the laser was about the transition energy of the heavy-hole exciton ground state of MSQWs. The transition energy of the exciton ground state of MSQWs was nearly independent of the bias voltage, but the absorption intensity of the exciton peak was considerably changed with the bias voltage due to a sensitive change in the oscillator strength.9 This property of MSQWs has been successfully utilized for self-electro-optic effect devices.3–5

We used the HP4145B parameter analyzer for $I-V$ measurements. The ac components of the electrical signals were extracted.

FIG. 1. $I-V$ curves of the pin diode at various laser power. The total capacitance of the diode was $\sim 2 \text{ pF}$. Note that the dark current was negligible on the scale of the figure. The inset represents the MSQW pinip diode for this study.
FIG. 2. (a) Electrical and optical oscillations in the pin diode at a bias voltage of 1.6 V, and (b) the spectral characteristics of the electrical oscillations at the same bias voltage: peak frequency = 57.9 MHz; span = 1 MHz; and input laser power = −6 mW.

The frequency spectrum of the intrinsic electrical oscillations of the diode at the same voltage reveals a sharp peak at 57.9 MHz, as shown in Fig. 2(b). The electrical and optical oscillations show approximately the same phase. The change in the reflected light and the contrast ratio of the oscillation amplitude were ~ 20% and ~ 2 for the laser input power of ~ 6 mW, respectively. These performances are comparable with those of other electroabsorption devices.4 The amplitude and phase of the optical oscillations are determined by the swing of the electric field in the intrinsic region of the pin diode where the electroabsorption of MSQWDs is sensitively modulated by the electric field. The amplitude of the optical oscillation is estimated by the proportion to the voltage width of the plateau.

When unstable circuit oscillations are suppressed with a capacitor connected to the diode, a unique high-frequency oscillation is observed for a given bias in a single plateau, as plotted by the solid line in Fig. 3. An interesting result, as plotted by the solid squares in Fig. 3, is that the frequency of the intrinsic oscillations increases continuously from ~ 54.5 to ~ 58.5 MHz as a function of the bias voltage under ~ 6 mW laser power. The oscillation frequency can also be tuned with the input laser power. Figure 4 shows that the oscillation frequency of the pin diode at 0 V increases from ~ 51 to ~ 60 MHz with increasing the laser power from ~ 3 to ~ 13 mW, respectively. The inset in Fig. 4 shows a simple equivalent circuit of the diode in the optical input scheme at zero external bias voltage.

Assuming the MSQWD has the same equivalent circuit as the RTD diode,10 we can analyze qualitatively the frequency tunability of the MSQWD at the stable condition. The oscillation frequency of the MSQWD is given by

\[
f = \frac{G_d}{2\pi C_d} \sqrt{\frac{1}{R_s G_d}} - 1 < f_r,
\]

where \(f_r\), \(G_d\), \(R_s\), and \(C_d\) are the cutoff frequency, NDC, series resistance, and diode capacitance, respectively, and determine the oscillation frequency of the diode.10 At a constant laser power, the \(C_d\) is decreased with the reverse bias.
voltage, whereas $G_d$ and $R_s$ remain fixed. Consequently, the frequency of the intrinsic oscillations can be tuned with the bias voltage. However, for a constant voltage, a variation of the input power is a more efficient way to control and change the dynamic status and electrical parameters of the pin diode structure, but the qualitative analysis of this effect is complicated. For this case, the accumulation of carriers in the MSQWDs increased with laser power and modifies the circuit parameters such as $R_s$ and $C_d$, but enhances dominantly the $G_d$ value. Therefore, both the amplitude and frequency of the optical oscillations increase with the laser power. Contrary to the electronic RTD devices, the oscillation characteristics of MSQWDs can be effectively tuned by both the optical and electrical controls.

In summary, we investigated the characteristics of photoinduced self-electro-optical oscillations in MSQWDs showing the NDC property under the illumination of a high power laser, and demonstrated that the frequency of intrinsic oscillations in the diode could be tuned effectively with the bias voltage and laser power. The intensity change in the reflected light and the contrast ratio of the oscillation amplitude were $\sim 20\%$ and $\sim 2$, respectively, which are comparable to those of other electroabsorption devices. The oscillation frequency and amplitude can be increased by optimizing the MSQWD structure and the tuning conditions. We believe that the photoinduced self-oscillations of MSQWDs have a great potential for electro-optical components such as the oscillator and modulator.

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