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Vanishing of Negative Differential Resistance Region Due to Electric Field Screening in Wannier-Stark Localization Type Self-Electro-Optic Effect Devices

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We report on the absorption saturation behavior of photocurrent versus reverse bias voltage characteristics (i-V characteristics) under high intensity optical pulse excitation in short-period superlattices. While a negative differential resistance (NDR) region in the i-V curve normally appears due to the Wannier-Stark localization effect under low intensity excitation, vanishing of the NDR was observed under high excitation. This phenomenon is caused by local electric field screening due to the charge separation of photogenerated carriers.

1. Introduction

In recent years, absorption saturation mechanisms have been actively investigated for semiconductor multiple quantum well (MQW) or superlattices (SLs) to use such structures under high optical excitation. In general, under high speed or high bit-rate operation, each optical pulse has a very high intensity photon flux. To confirm the high speed operation, a large amount of photo-generated carriers must be swept out from the MQW or superlattice active region so as to not saturate the optical absorption. Especially for opto-electronic devices such as self-electro-optic effect devices (SEEDs)[1] that use an MQW structure, saturation behavior related to exciton saturation mechanism[2] and carrier escape process from quantum well (QW)[3] has been actively studied. In these MQW type devices, the barrier width is rather thick. Therefore, the photo-generated carriers usually escape from the QW by a thermionic emission process as represented by the extremely shallow quantum well[4], and the carriers are then swept out through a continuum state or above barrier states. On the contrary, for a superlattice device with a thin barrier width, carriers run mainly below the barrier by tunneling. There have been few reports on carrier transport processes and on absorption saturation mechanisms in thin-barrier superlattices (SLs) under high intensity optical excitation. Such research is expected to be useful in opto-electric devices using shortperiod superlattices (SPSLs), for example, SEEDs based on Wannier-Stark localization[5-7]. In this letter, we report on the absorption saturation behavior of photocurrent (Pc) versus reverse bias voltage characteristics (i-V characteristics) under a high optical pulse excitation intensity in shortperiod superlattices that show the Wannier-Stark localization (WSL) electro-optic effect. While a negative differential resistance (NDR) region normally appeared due to the WSL effect in the i-V curve under low intensity excitation, vanishing of the NDR was observed under high excitation. This phenomenon is caused by local electric field screening due to charge separation of the photogenerated carriers.

2. Experiment

We used a 100-period intrinsic GaAs/AlAs (42 Å/8.5 Å) superlattice contained in a p-i-n diode structure. The sample was grown on a (100)-oriented n^+-GaAs substrate by molecular beam epitaxy (MBE). After an 800-nm width n^+-GaAs (~2×10^{18} Si doping) buffer layer was grown on the substrate, a nominally undoped superlattice layer consisting of 100 periods of GaAs/AlAs with GaAs QW widths of 42 Å (15 monolayers) and AlAs barrier widths of 8.5 Å (3 monolayers) was grown with 10-nm GaAs undoped cladding layers on both sides. A 50-nm width p-cap layer was then grown with p^+-GaAs (~5×10^{18} Be doping). The sample was fabricated into p-i-n diode mesas of 50 μm square. Alloyed Au electrodes were prepared to apply the electric field to the intrinsic region and the ohmic contact was confirmed by examining the forward biased current-voltage characteristics.

An 0.8 MHz repetition rate, 1-ps pulse-width ultrashort light pulse from a mode-locked wavelength-tunable Ti:sapphire laser irradiated the sample through a microscope with a 10x to 50x objective lens, thus increasing the optical excitation density with about a 20-μm down to a 4-μm e^{-2} beam diameter. In all of the experiments described later, the optical pulse was injected from the p-cap side. The sample was biased with a constant voltage source and the current limit function was turned off to avoid deforming the photocurrent transient. A high-frequency-type chip-condenser was used as a bypass condenser to improve the electrical circuit characteristics at a fast response time. It was mounted next to the p-i-n diode sample on a sapphire plate and was connected to the signal-GND and n-electrode

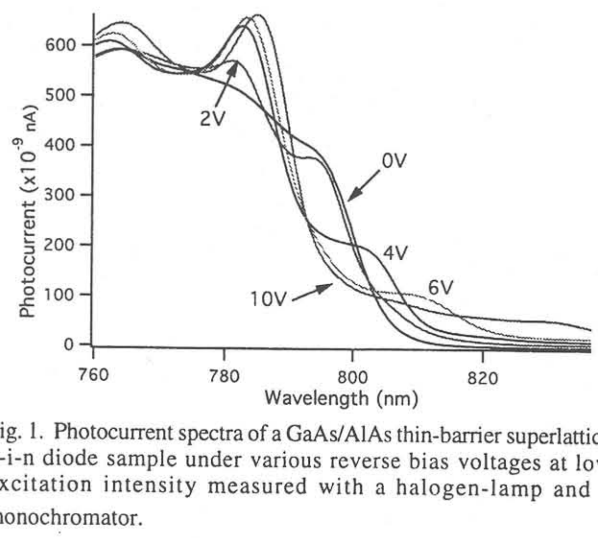

Fig. 1. Photocurrent spectra of a GaAs/AlAs thin-barrier superlattice p-i-n diode sample under various reverse bias voltages at low excitation intensity measured with a halogen-lamp and a monochromator.

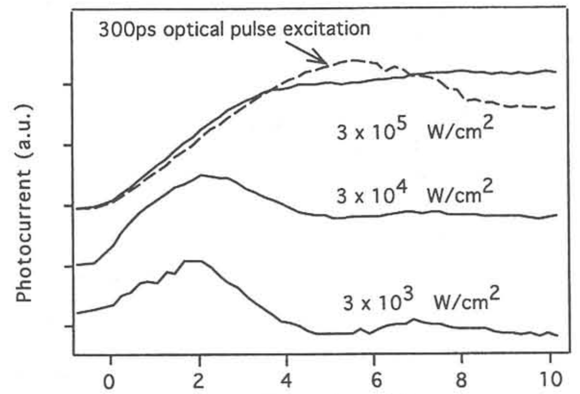

Fig. 2. Photocurrent versus reverse bias voltage characteristics at a 0.8 MHz repetition rate, 795-nm wavelength, and 1-ps light pulse irradiated from a mode-locked Ti:sapphire laser. Excitation intensity is indicated in the figure.

connected to the power supply cable. The Pc signal from the p-electrode was connected to a high-frequency coaxial cable, measured with a sampling-oscilloscope (Tektronix S-6 sampling head), and terminated by the internal 50 Ω resistor of the oscilloscope. A triggering system having low timing-jitter (Hamamatsu C4792 and C1808) generated a trigger signal from the laser light pulse, and could reduce the timing jitter down to about 20 ps.

3. Results and Discussion

Figure 1 shows normal photocurrent (Pc) spectra under low optical excitation of the sample affected by the Wannier-Stark localization effect. Under near flat-band condition (+1.5 V bias), the Pc spectra shows miniband structure. For an electric field strong enough to decouple the resonance (above 2 V), the Pc spectra becomes that of a isolated QW by the WSL effect, and the absorption band-edge shows a blue shift by 0.5(ΔE1+ΔH1), where ΔE1 and ΔH1 are miniband width of conduction and valence bands, respectively[5,6]. If the input wavelength is tuned to near this band-edge region, these shortperiod superlattices can switch the light by an externally applied bias voltage; for example, the operation of SEEDs with the Wannier-Stark localization effect as bistable optical switching devices has been reported[7]. In this condition, the i-V characteristics show the NDR due to the decrease of the optical absorption[7] caused by the WSL effect.

Figure 2 shows the NDR region in the i-V curves under various excitation intensities. In contrast to the ordinary NDR region under low excitation, they shifted to a higher bias voltage and vanished as the excitation intensity increased. Note that when the same intensity and a long duration optical pulse (~300 ps) were used, the vanished NDR again reappeared at a higher bias voltage than normal for NDR. Considering the use of a 1-ps optical pulse, this restoration implies a carrier escape time faster than 300 ps, but slower than 1 ps to reduce the absorption saturation. The shift of the NDR toward a higher bias voltage indicates an influence from the space charge screening by the photogenerated carriers. The vanishing of the NDR means that the absorption band-edge does not make a blue-shift and that the optical absorption rate does not change for the external applied voltage. Owing to the space charge screening by the amount of the photogenerated carriers, the inner electric field in a

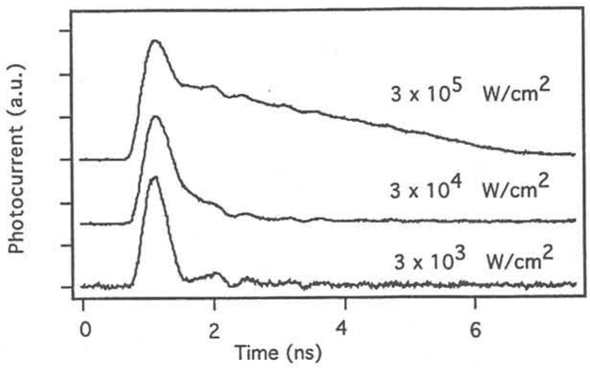

Fig. 3. Impulse response of photocurrent at a -0.2 V reverse bias, 0.8 MHz repetition rate, 720-nm wavelength, and 1-ps light pulse from a mode-locked Ti:sapphire laser with about a 20 μm e^{-2} beam diameter. Excitation intensity is indicated in the figure.

superlattice cannot change to perform the WSL effect. Therefore, the competition between sweep-out time from the QW and the production rate of the photogenerated carrier must occur on the order of 1 ps.

Figure 3 shows a time-resolved Pc response under various excitation intensities at 300 K for a reverse bias voltage of -0.2 V. In contrast to an ordinary Pc under low excitation, a slow decay component appeared in the tail of the Pc transient as the excitation intensity increased. Vanishing of the NDR was also observed when the slow Pc component appeared. Simultaneously, an increase in the PL lifetime was observed; the PL eventually showed a non-exponential decay tail. Figure 4 shows the relation of both Pc and PL temporal profiles in the high excitation regime. Apparently shown is the end point of the slow Pc tail and the disappearing timing of the non-exponential decay of the PL coincide. This implies that residual carriers remaining in the superlattice region have a slow escape rate due to a lower electric field than the externally applied one. From the convex shape of the PL temporal response, it is known that once the number of stagnated carriers decrease and become lower than a value by radiative recombination and degraded sweep-out, electric field screening becomes weak and improved sweep-out dominates the reduction process. Then, carriers are swept out rapidly, which makes the PL decay fast.

To examine the space charge screening of the electric field in the intrinsic superlattice region, a simulation based on 1-D Green's function method for electric potential[8] was applied. Figure 5 shows the simulated result under a 10^{11} / cm^2 carrier density; initial spatial distribution is an exponential decay curve from the p-cap side having approximately a 10^4 / cm absorption coefficient of the incident 720 nm wavelength. The reduction of the electric field slows down the carrier sweep-out (mainly for electrons) from the SL region. Consequently, that causes the saturation and the persistence of Pc and PL as shown in Figs. 3 and 4. In this simulation, effective drift velocity of electron and heavy-hole are assumed to be about 100 fs and 10 ps, respectively. These drift velocities are deduced from the non-sequential resonant tunneling time[9], which did not vary so much when the electric field corresponding to the reverse bias was varied. As shown in Fig. 5, because the electron drift velocity is so fast, electric potential of most of the superlattice area was flattened by the screening till 3 or 4 ps after the generation of the electron-hole pair. Because the movement of the hole is very slow

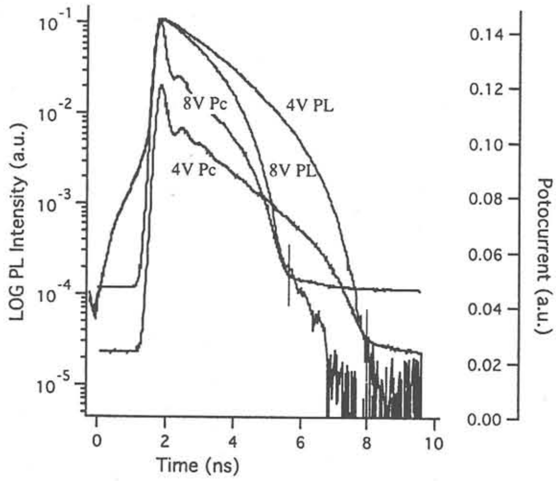

Fig. 4. Time-resolved photocurrent and photoluminescence spectra of a shortperiod superlattice reverse biased to 4 and 8 V. The excitation intensity was ~300 kW/cm^2.

compared to that of the electron, the distribution of the hole cannot change in this time range. This time-independent distribution of heavy-holes tend to cause the screening. Another calculation under the condition of 430-nm wavelength showed a different characteristic. In this case, the endurance of screening for the carrier density was high because the stationary hole position is gathered near the p-cap region.

Concerning the above experimental and simulated results, the mechanism of the absorption saturation phenomenon, i.e., vanishing of the NDR, can be considered as follows: There seems to be two different screening processes of fast and slow mechanisms. The latter is screening by the charge separation represented in Fig. 5. The slow process exhibits its power a few picoseconds after photocarrier generation and the function is simple. The origin of the fast process is much complex. From Fig. 2, the saturation process is faster than the 1-ps optical pulse width. In other words, the absorption saturation occurs in 1 ps, because the vanishing of the NDR already exists under a 1-ps optical pulse excitation, but not for a 300-ps pulse width. Therefore, origin from macroscopic carrier transport should be excluded. As shown in Fig. 2, from the shift toward higher bias voltage of the NDR region by increasing the excitation intensity, space charge screening is implied. The voltage shift cannot be explained by the band-gap re-normalization and device heating, because in this case, the shift will move toward a lower voltage. In addition, Fig. 2 shows that almost equal quantities of the photocurrent are output under both 1-ps and 300-ps optical pulse excitation. This excludes origin from band-filling, because in the case of state-filling, photocurrent in the 1-ps condition must be small. From the above consideration, it is most plausible to think that local field screening can be established from the electron-hole plasma in the QW or near there. From about 300 fs exciton ionization time described in Ref. 2, it is considered that the screening is made by separated electron and hole in a picosecond time range. Although there remains room for discussing the subject of the local space charge screening in QW, we would like to complete the discussion by showing other evidence that was found by us quite recently. We found that the X state in the AlAs barrier sufficiently influences carrier transport even in type-I superlattices[10]. Because the transfer to the X state in barriers has a strong scattering cross-

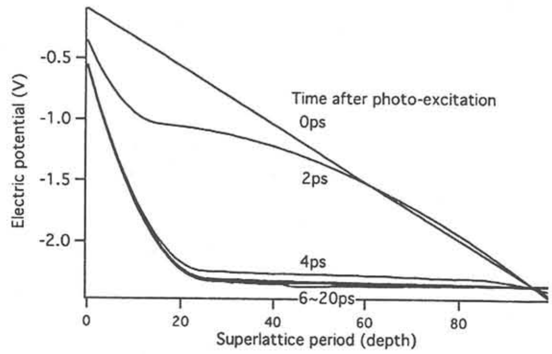

Fig. 5. Deformation of electric field potential due to screening by charge separation of high density electrons and holes under -1 V reverse bias voltage. The positive direction of the potential is downward as ordinarily drawn in the band diagrams of semiconductors.

section for the Γ state in the well, in thin barrier superlattices used for WSL-SEEDs, a soaked electron wave function from the QW will suddenly be trapped by an X state in remote barriers. It is also reasonable that this sudden trapped electron is the origin of the local space charge.

4. Conclusion

In summary, space charge screening behavior of WSL-SEEDs were studied. Experimental results, i.e., vanishing of the NDR region and the anomalously persistent PL and Pc tail were explained by simulated electric filed screening mechanism and the consideration of the charge separation and the local space charge establishment.

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