Photocurrent self-oscillations in a direct-gap GaAs-AlAs superlattice

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Undamped photocurrent self-oscillations have been observed in a direct-gap GaAs-AlAs superlattices. The oscillations in the MHz regime appear over a wide voltage range, where the time-averaged I-V characteristic exhibits a strong negative differential conductivity. The frequency distribution is strongly dependent on the applied voltage and the laser intensity. © *1997 American Institute of Physics.* [S0003-6951(97)04003-5]

Self-oscillations of the current in doped[1–4] and of the photocurrent in undoped, photoexcited superlattices[5–7] with rather weak coupling have been reported very recently. The origin of these current self-oscillations is an oscillating charge accumulation layer, the domain boundary, separating two regions of rather well-defined electric fields, the low- and high-field domain. The photocurrent oscillations have been observed in an undoped, indirect energy gap GaAs-AlAs superlattice (SL), i.e., the lowest conduction band state is formed by the X states in the AlAs barriers. In undoped, direct gap SLs so far only damped oscillations of the photocurrent have been reported.[8] Since the recombination lifetime in direct gap SLs is much shorter than in indirect gap SLs, it is more difficult to observe undamped oscillations of the photocurrent, since they can only be detected at much higher frequencies (several GHz).

In this paper we report the observation of photocurrent self-oscillations in the MHz regime in an undoped, direct energy gap GaAs-AlAs SL. The oscillations of the photocurrent appear in a voltage region, where the time-averaged I-V characteristic exhibits several regions of negative differential conductivity. The frequency distribution of the oscillation amplitudes varies drastically not only with the applied voltage, but also with the laser intensity. The existence of these undamped oscillations is probably connected with electric-field domain formation, where the high-field domain is due to a Γ-X resonance between the well and barrier material.

The undoped SL contains 100 periods of 6.2 nm GaAs and 3.4 nm AlAs. It is embedded in a p^+-i-n^+ structure, which is grown on a (100)-oriented n^+-GaAs substrate by molecular beam epitaxy (MBE). Starting from the substrate the layer sequence contains an n^+-GaAs (0.2 μm, 10^{18} cm^{-3} Si doping) buffer layer, an n-$Al_{0.4}Ga_{0.6}As$ (1 μm, 5×10^{17} cm^{-3} Si doping) cladding layer, the intrinsic layer consisting of the undoped superlattice sandwiched between undoped 500 Å $Al_{0.4}Ga_{0.6}As$ cladding layers, a p^+-$Al_{0.4}Ga_{0.6}As$ (0.2 μm, 10^{18} cm^{-3} Be doping) cladding layer, and a p^+-GaAs (10 nm, 5×10^{18} cm^{-3} Be doping) cap layer. The sample is processed into 50 μm square mesas with alloyed Au electrodes as contacts. A cw He-Ne laser (632.8 nm) focused onto the p^+-contact through a microscope objective with a spot diameter of about 20 μm is used to excite carriers in the SL. Using an absorption length of 200 nm and a carrier lifetime of 1 ns, a laser intensity of 1 mW corresponds to a two-dimensional carrier density on the order of 10^{10} cm^{-2} per quantum well. The oscillations of the photocurrent are detected at low temperatures (between 20 and 160 K) in a closed-cycle cryostat using a sampling oscilloscope (Tektronix 7854) and a spectrum analyzer (HP 8566B). The time-averaged I-V characteristics are measured with a semiconductor parameter analyzer (YHP4145B). The sample is biased in the reverse direction so that no carriers are injected from the contacts. We will denote the reverse bias voltage as a positive number.

In Fig. 1 the time-averaged photocurrent measured at 80

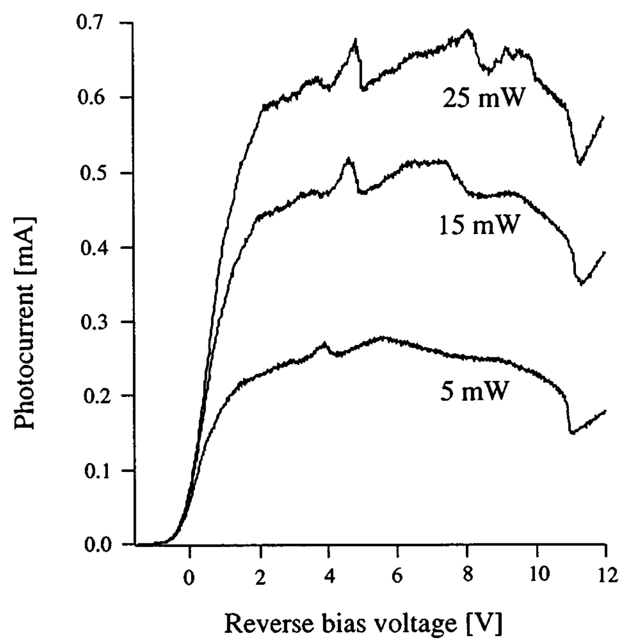

FIG. 1. Time-averaged photocurrent vs applied reverse bias voltage for three different laser intensities at 80 K.

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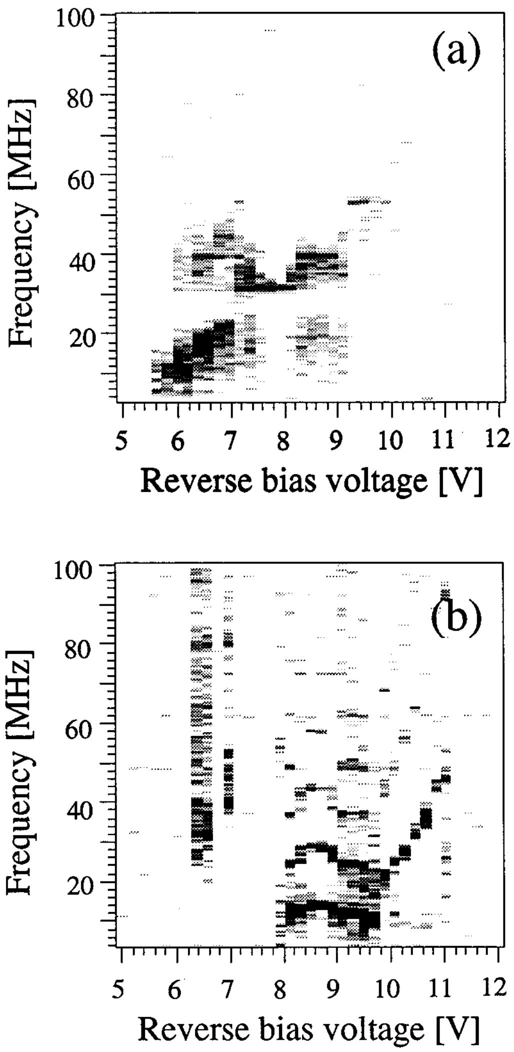

FIG. 2. Power spectra of photocurrent self-oscillations vs applied reverse bias voltage for a laser intensity of (a) 5 and (b) 25 mW at 80 K. Black areas correspond to large amplitudes.

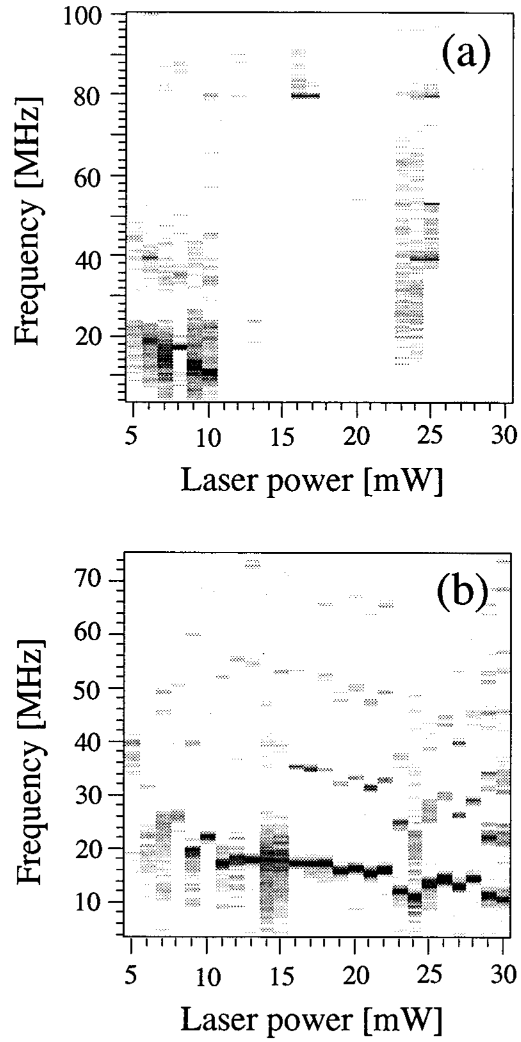

FIG. 3. Power spectra of photocurrent self-oscillations vs laser power for a reverse bias voltage of (a) 7 and (b) 9 V at 80 K.

K is plotted as a function of the reverse bias voltage for three different laser intensities. The photocurrent for all three laser intensities clearly exhibits several regions of negative differential conductivity. However, the strongest reduction in current at about 11 V can be observed for almost any laser intensity in this range. The superlattice has a direct energy gap of 1.617 eV, the subband spacing between the first and second conduction in GaAs is 245 meV, while the energy spacing between the first Γ-subband in the GaAs well and the first X-subband in the AlAs barrier is 116 meV. Converting these numbers into voltages leads to resonance voltages of 23 V for $\Gamma_1 \rightarrow \Gamma_2$ tunneling and 21.7 V for $\Gamma_1 \rightarrow X_1$ tunneling. Both resonance voltages are much larger than the displayed voltage range in Fig. 1. The origin of the strong reduction in the photocurrent at about 11 V is therefore not known.

In the voltage region of Fig. 1 the photocurrent exhibits undamped self-oscillations, when the laser intensity is larger than 5 mW. Figure 2 shows the frequency spectrum as a function of voltage at 80 K for two laser intensities, 5 mW in (a) and 25 mW in (b). While at 5 mW the oscillations occur only between 5.5 and 9 V, a laser intensity of 25 mW leads to a very different distribution of the oscillatory regime within the displayed voltage range. While for some voltages the oscillations are dominated by a fundamental frequency with some higher harmonics [8.6 V in Fig. 2(b)], the distribution of frequencies can also be rather broad as for 6.4 V in Fig. 2(b). There are also voltage windows in Fig. 2(b), where no oscillations are detected, e.g., between 7.0 and 7.8 V. The frequency distribution therefore depends strongly on the applied voltage.

This behavior becomes even more evident, when the frequency spectrum is plotted versus the laser intensity for a fixed applied voltage. In Fig. 3(a) the frequency spectrum is shown between 5 and 30 mW for an applied voltage of 7 V at a temperature of 80 K. Oscillations are observed between 5 and 10.5 mW, around 15 mW at a much higher frequency, and between 23 and 25 mW. This behavior changes drastically when the voltage is changed to 9 V as shown in Fig. 3(b). For this voltage oscillations are present over the whole intensity range with a fundamental frequency between 10 and 20 MHz, which decreases with increasing laser intensity. However, the spectral distribution, i.e., the amplitude of the higher harmonics, varies significantly for different laser intensities. There may be chaotic windows in the frequency spectra of Figs. 2 and 3, which have been observed recently in the self-oscillation spectra of a doped GaAs-AlAs SL.[9,10] In order to verify the existence of these chaotic windows additional experiments at lower temperatures have to be performed.

The self-oscillation spectra of the photocurrent can be measured up to 160 K. Above this temperature, no oscillations are detected. The oscillations persist at lower temperatures down to 15 K, which is the limit of our cryostat. The detailed frequency distribution also changes with temperature, but qualitatively the spectra look similar to the 80 K spectra. Further experiments in a flow cryostat are necessary to investigate the behavior at low temperatures.

Although we do not have direct evidence from optical measurements that the SL exhibits electric-field domain formation in this voltage and carrier density range, we believe that the oscillations are caused by a moving domain boundary. The reason for the detection of undamped photocurrent oscillations in this direct gap SL with frequencies in the MHz regime is probably connected with the nature of the high-field domain. In this SL it is possible that the high-field domain is formed by a resonance of Γ_1 subband states in the GaAs well and X_2 subband states in the AlAs barrier separated by 1.5 SL periods. According to our calculation, this resonance should occur at approximately 11 V. A resonance between Γ and X states would result in prolonged recombination lifetimes for carriers in the high-field domain, which then would make it possible to detect undamped photocurrent oscillations in the MHz regime.

In summary, we have detected undamped self-oscillations of the photocurrent in the MHz regime in an undoped, direct gap GaAs-AlAs superlattice. The frequency spectra are strongly dependent on the applied voltage and the laser intensity. A high-field domain caused by the resonant interaction of the lowest Γ state in the GaAs well and an X state in the AlAs barrier is probably responsible for the undamped nature of these oscillations.

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