Current self-oscillations in photoexcited type-II GaAs-AlAs superlattices

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Self-oscillations of the photocurrent have been observed in type-II GaAs-AlAs superlattices. In addition to the fundamental frequency, several higher harmonics are present. The frequency of the oscillations can be tuned for a fixed carrier density from 15 to 120 MHz by simply changing the applied bias. The frequency distribution within a certain voltage range can be varied by changing the density of photoexcited carriers. For larger carrier densities, higher frequencies are observed in a different voltage range. This system could therefore be used as a high-frequency oscillator, which can be controlled by two external parameters, the applied voltage and the light intensity. [S0003-6951(96)01530-6]

Weakly coupled superlattices (SLs) exhibit oscillating electric-field domain formation resulting in self-oscillations of the current.[1–4] However, these self-oscillations are only observed in weakly to strongly doped superlattices. In undoped, photoexcited SLs so far only damped oscillations of the photocurrent have been observed.[5] A possible reason for the damped nature of the oscillations in photoexcited systems might be the rather long oscillation periods compared to the recombination lifetime. However, in indirect gap SLs the recombination lifetime for photoexcited carriers increases drastically so that the oscillation period can easily be below the carrier lifetime.

In this letter, we will present the observation of self-oscillations of the photocurrent in an undoped GaAs-AlAs SL with an indirect band structure. The electron transport in this system is dominated by tunneling between X-subbands in the AlAs layer. Current oscillations appear within a certain range of the applied voltage and of the photoexcited carrier density. The frequency of the oscillations can be tuned via the applied voltage or the laser intensity. The oscillations are due to an oscillating domain boundary between two electric-field domains.

The undoped SL contains 75 periods of 3.4 nm GaAs and 5.1 nm AlAs. It is embedded in a n-i-n structure, which is grown on a (100)-oriented n^+-GaAs substrate by molecular beam epitaxy (MBE). The contact layers near the substrate and surface are 0.2 μm n^+-$Al_{0.4}Ga_{0.6}As$ layers with a Si doping density of 5×10^{17} cm^{-3}. A 0.2 μm buffer layer of n^+-GaAs with a doping density of 2×10^{18} cm^{-3} is inserted between substrate and bottom contact layer, and a 50 nm n^+-GaAs layer with 2×10^{18} cm^{-3} Si doping is used as a 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 n^+-GaAs cap layer 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 of about 1.8×10^{10} cm^{-2} per quantum well. The oscillations of the photocurrent are detected at low temperatures (20 K) in a closed-cycle cryostat using a sampling oscilloscope (Tektronix 7854) and a spectrum analyzer (HP 8566B). The time-averaged I-V characteristics is measured with a semiconductor parameter analyzer (YHP4145B).

Self-oscillations of the photocurrent occur for a negative bias applied to the substrate. In Fig. 1 the time-resolved current (a) and its power spectrum (b) measured simultaneously with a spectrum analyzer are shown at -3 V for a laser intensity of 2.5 mW at 20 K. The oscillations are undamped and clearly contain in addition to the fundamental frequency of 34 MHz at least two higher harmonics. These oscillations are detected only for laser intensities between 0.5 and 8 mW. Since the dark current of this sample in this voltage range lies in the sub-pA regime, the current oscillations ride on a much smaller background signal than in doped superlattices without any photoexcitation. However, even in this photoexcited system, the average current is not zero since electrons and holes move in opposite directions resulting in a finite average current in accordance with the applied electric field.

We have measured the frequency spectrum using a spectrum analyzer over the whole voltage range. For a laser intensity of 2 mW, the oscillations are observed between -1.5 and -4.8 V. We looked for oscillations up to -20 V, but could not detect any beyond -4.8 V for a laser intensity of 2 mW. From a comparison of the photoluminescence spectra with a calculation of the energy band structure for this superlattice, the dominant transport mechanism in this voltage range are tunneling resonances between $X_1 \rightarrow X_1$ as

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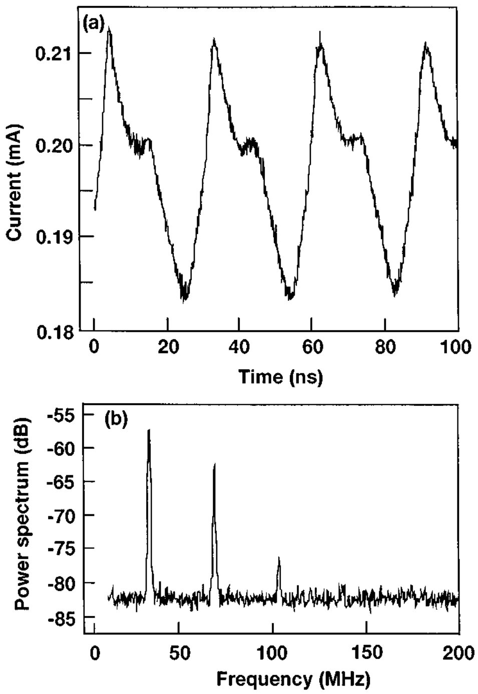

FIG. 1. (a) Current self-oscillations and (b) corresponding power spectrum at −3 V for a laser intensity of 2.5 mW at 20 K.

well as $X_1 \rightarrow X_2$. A detailed description of the origin of domain formation in this type-II SL can be found in Ref. 6.

The voltage dependence of the frequency spectrum is shown in Fig. 2 for a laser intensity of 2 mW. There is a very strong dependence of the oscillation frequencies on the applied voltage between −1.5 and −1.8 V. The frequency changes almost by one order of magnitude in this range. Between −1.8 and −3.5 V the frequency is rather constant, but increases again beyond −3.5 V until the oscillations disappear at about −4.8 V. This strong change in oscillation frequency is very similar to the results on the voltage dependence of domain formation times in doped SLs.[7] We therefore attribute the narrow field range with the strongly de-

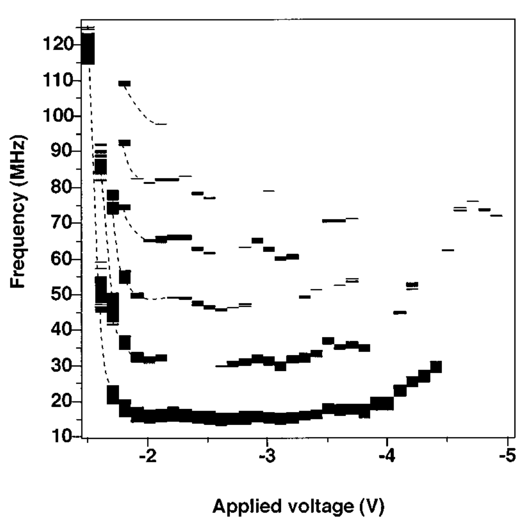

FIG. 2. Power spectra of self-oscillations vs applied voltage for a laser intensity of 2 mW at 20 K. Black areas correspond to large amplitudes. The dashed lines have been added as a guide to the eye.

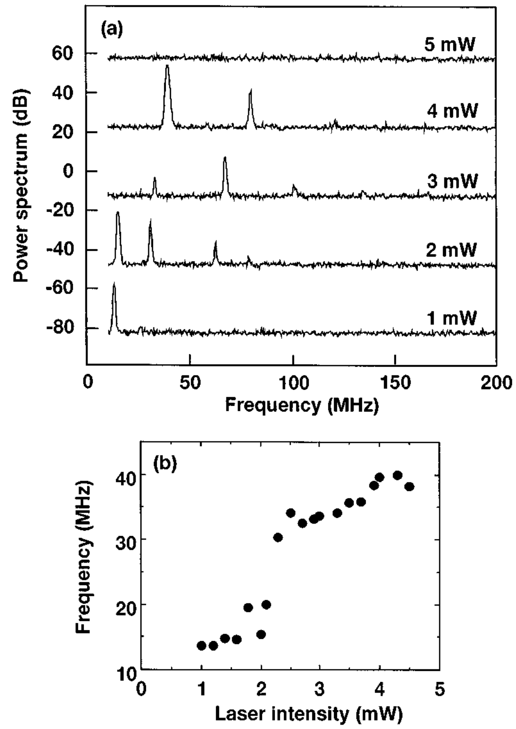

FIG. 3. (a) Power spectra of self-oscillations for −3 V for different laser intensities between 1 and 5 mW at 20 K. The different spectra have been shifted by 35 dB with respect to each other in order not to overlap. (b) Fundamental frequency vs laser intensity for −3 V at 20 K.

creasing frequency to the true negative differential resistance region of the drift velocity versus electric field characteristics. The origin of the increase of the frequencies at large fields is probably due to a decreasing propagation distance, when the domain boundary is closer to the contact region.

The intensity distribution of the higher harmonics varies quite strongly over the whole voltage range. It has recently been shown that fluctuations of layer thickness and doping profile can have a very strong effect on the self-oscillations in doped superlattices.[8] Since this superlattice is undoped, only fluctuations of the GaAs and AlAs layer thickness can be present. However, even the quality of the interfaces could vary between different periods, which would also affect the frequency distribution.

For photoexcited systems there are actually two external parameters, which can be varied, the applied voltage and the carrier density. In Fig. 3(a) several frequency spectra are shown for a fixed applied voltage varying the laser intensity between 1 and 5 mW. The fundamental frequency strongly increases with increasing carrier density between 1.5 and 2.5 mW and then saturates as shown in Fig. 3(b). Since the frequency of the oscillations is determined by the tunneling time and the number of superlattice periods, which the domain boundary is covering during one oscillation period,[1,2,4] the increasing frequency is probably due to a decreasing spatial extent of the oscillating domain boundary. At the same time, the power distribution between the frequencies also changes with varying laser intensity. For this applied voltage the oscillations disappear for laser intensities of 5 mW or more. We therefore expect stable domain formation under these excitation conditions.

The oscillations disappeared for laser intensities above 8 mW for all bias voltages between -1.5 and -4.8 V. However, for larger laser intensities of 15 to 20 mW, self-oscillations appeared at much larger electric fields between -15 and -20 V as well as in the positive bias direction in the same voltage range. The fundamental frequency of these oscillations is drastically increased to 155 MHz, while the higher harmonics extend to 600 MHz. While the oscillations at small electric fields have been assigned to domain formation due to the tunneling $X_1 \rightarrow X_2$, these oscillations originate from resonant transfer from X_1 to Γ_1. Since this transfer occurs at much larger fields than resonant tunneling between X_1 and X_2,[6] the oscillation frequency is expected to be much larger. Furthermore, since the space charge layer forming the domain boundary has to contain a larger density for large fields, this oscillating regime is expected to occur at higher carrier densities.

The observation of undamped photocurrent oscillations in type-II SLs is probably connected with the increased carrier lifetime in indirect gap SLs. While in type-I SLs the recombination lifetime is typically of the order of 1 ns, it increases in type-II SLs to the microsecond regime.[9] Since the oscillation periods in previously reported investigations are typically between 10 and 100 ns, carriers recombine before the domain boundary can complete a full oscillation. However, due to the increased lifetime in type-II SLs it is possible for the domain boundary to complete an oscillation before the carriers recombine.

In summary, current self-oscillations have been detected in an undoped, photoexcited type-II superlattice. The frequency can be tuned over a wide range either by changing the applied voltage or varying the photoexcited carrier density. The observation of these oscillations in a type-II superlattice clearly demonstrates that the recombination lifetime of the photoexcited carriers is an essential parameter. Photocurrent oscillations should therefore also be present in type-I superlattices, if the period of the oscillations is adjusted to be faster than the recombination lifetime.

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