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Strong Electric Field Driven Carrier Transport Non-Linearities in n-Type GaAs/AlGaAs Superlattices

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Nanosecond pulsed technique was used to study and discriminate strong electric field induced effects in carrier transport in silicon doped GaAs/$Al_{0.3}Ga_{0.7}As$ superlattices at room temperature. The experiment shows that the superlattice can serve as gain media to employ parametric phenomena for microwave amplification.

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1. Introduction

Semiconductor superlattices (SL) are artificial structures which can be used as essential ingredients in modern devices, for instance, quantum cascade lasers [1] or serve as an attractive environment to study various quantum phenomena in a solid state. As a beautiful illustration of the latter one can mention terahertz (THz) emission from the Bloch oscillations [2] which can be understood as quantum beats with spatial displacement between the Wannier–Stark states [3] in SL biased up to 10–20 kV/cm. In contrast to quantum cascade lasers whose emission is typically fixed to a certain wavelength, the emission spectra originating from the Bloch oscillations in optically-pumped SL is broadband and electric field-tunable, thus, it can be employed to design a new type of device. This, the so-called Bloch laser — an electrically pumped and wavelength-tunable THz emitter — still does not exist. The experimental realization of such a device meets, however, huge difficulties. On the one hand, the observation of the Bloch oscillations requires high fields or long scattering times since the period of a periodic oscillating wavepacket must be shorter than the carrier scattering time [3]. On the other one, the electrical injection of carriers into the Wannier–Stark states requires the biasing of the structure to the regime with negative differential resistance (NDR), which hinders the realization of a homogeneous field distribution across the SL. In order to circumvent the obstacles one needs to look for other approaches suited for the employment of SL as amplifying media. Recently, it was suggested that SL can be successfully used as parametric gain environment for achieving room temperature THz emission [4], moreover, it was shown that parametric gain does not require NDR [5]. It is worth noting that the latter is an inherent feature of superlattices tuned to the Bloch gain regime [6].

In this communication, we therefore investigate carrier transport features in silicon doped GaAs/$Al_{0.3}Ga_{0.7}As$ wide miniband SL with built-in field under application of strong 10–140 ns duration dc electric fields effects and microwave radiation of 10 GHz frequency at room temperature. The obtained results show that the studied structure can serve as gain media. The nanosecond scale measurements allow one to discriminate the Wannier–Stark states (the Esaki–Tsu regime) in direct bias and sequential resonant tunneling effects in a reverse biased structure.

2. Samples and experimental details

The structure is molecular beam epitaxy grown n-type GaAs/$Al_{0.3}Ga_{0.7}As$ superlattice consisting of the following sequences of layers: 30 nm GaAs cap layer/30 periods of SL consisting of 5 nm GaAs wells (silicon-doped, 10^{16} cm^{-3}) and 1 nm $Al_{0.3}Ga_{0.7}As$ barriers/25 nm GaAs/100 nm $Al_xGa_{1-x}As$: silicon doped $2\times10^{18}\rightarrow 2\times10^{16}$ cm^{-3}; $x = 0.3 \rightarrow 0.0$/800 nm $Al_{0.3}Ga_{0.7}As$: silicon doped 2×10^{18} cm^{-3}/100 nm $Al_xGa_{1-x}As$: sili-

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con doped 2×10^{18} cm^{-3}; $x = 0.3 \to 0.0$/100 nm GaAs (silicon-doped, 2×10^{18} cm^{-3})/n^+-GaAs substrate. The miniband width is about 100 meV.

The top electrical contact was formed by the evaporation of a Ti/Au compound followed by rapid thermal annealing (Schottky-type, built-in voltage is about 0.75 V). The bottom electrical contact was formed using Au/Ge/Ni alloy (ohmic-type) deposited from the n^+ substrate side. Mesas of the areas 80×80 μm^2, 40×40 μm^2 and 2 μm height were formed by conventional optical lithography and wet etching.

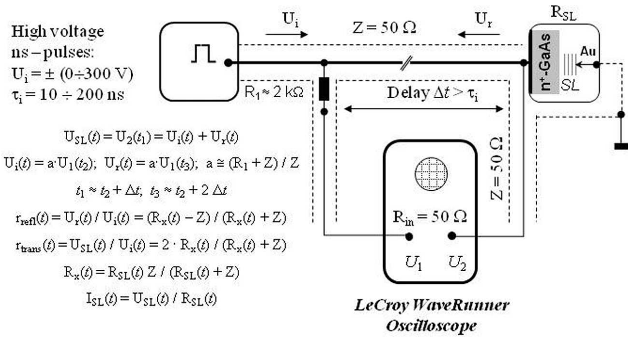

Fig. 1. Experimental setup for current–voltage characteristic measurements using nanosecond duration electrical pulses. $U_{\mathrm{SL}}, U_{\mathrm{i}}, U_{\mathrm{r}}$ denote voltage over the sample, voltage of incident and reflected pulses, respectively, R_{SL} and Z are sample resistance and impedance of the line, r_{refl} and r_{trans} are reflection and transmission coefficients, R_x is resulting resistance of two transmission lines in parallel.

The setup for measurements of current–voltage characteristics in nanosecond time scale and the formulae for estimations are given in Fig. 1. The samples for nanosecond-pulsed study of dc current–voltage characteristics were connected to the pulse source via a tee connector with two 50 Ω lines in parallel. In microwave experiments, SLs were placed into a rectangular waveguide (not shown here). All the experiments were performed at room temperature.

3. Results and discussion

Typical transients of the voltage pulse over the sample under direct bias are shown in Fig. 2. As one can see, under voltages below 3.7 V the traces have a similar rectangular pulse shape which is proportional to generator output pulse, while for applied bias with an amplitude higher than 3.7 V peculiarities in pulse distortion over the sample become pronounced. This can be associated with space charge formation induced by high electric fields and current instability effects appearing in nanosecond time scale. One can note that their signatures are also visible in extracted I–V characteristics above 3.7 V bias value. The range of electric fields which is free of domain formation deserves a particular interest.

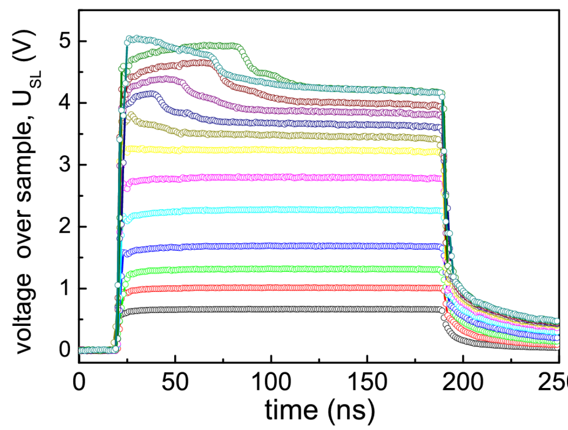

Fig. 2. Oscilloscope traces of the voltage pulse over the superlattice. Note the change of the trace in the voltage range above 3.7 V.

With this aim I–V characteristics were measured within a wide range of electric fields. Experimental results obtained with pulses of different duration — 30 ns and 140 ns — are shown in Fig. 3. Two characteristic regions, symbolically separated by the voltage value of 1 V (inflection point) can be distinguished (Fig. 3a). The first one, below 1 V, is mainly defined by the presence of a Schottky barrier. The second part, above 1 V exhibits high sublinearity. This sublinearity may be explained as a superposition of two mechanisms: the onset of negative differential velocity v [7, 8] and the exponentially growing carrier density controlled by the Schottky contact injection. Since there is no NDR, this regime is an electric-field domain-free zone suitable for gain or generation of high-frequency oscillations.

Noteworthy is the fact that nanosecond pulsed technique allows one to apply electric fields which are strong enough for achieving the Wannier–Stark resonances even in forward bias. It is illustrated by the inset of Fig. 3a, where the differential conductance is plotted as a function of the applied voltage. Near 3 V bias which roughly corresponds to the electric field of 18 kV/cm one can observe a clear pronounced peak in differential conductance. This effect can be attributed to the Wannier–Stark states in SL. The dependence of the electric conductance on the applied voltage given in the inset is dressed by non--equidistantly (due to the non-uniform built-in field) distributed spikes related to the sequential resonant tunneling already observed in SL below 30 K [9].

The reverse bias part (Fig. 3b) represents a typical Schottky contact characteristic followed by sharply expressed S-shape behaviour above 7 V in a longer time scale. It is supposed to be associated to the current instabilities in SL/contact interface.

Finally, it is worth noting that applied 10 GHz microwave radiation (data is not shown) induces an electromotive force signal which is linearly dependent of incident power and exceeds 2 V at 5 W. This experimental fact

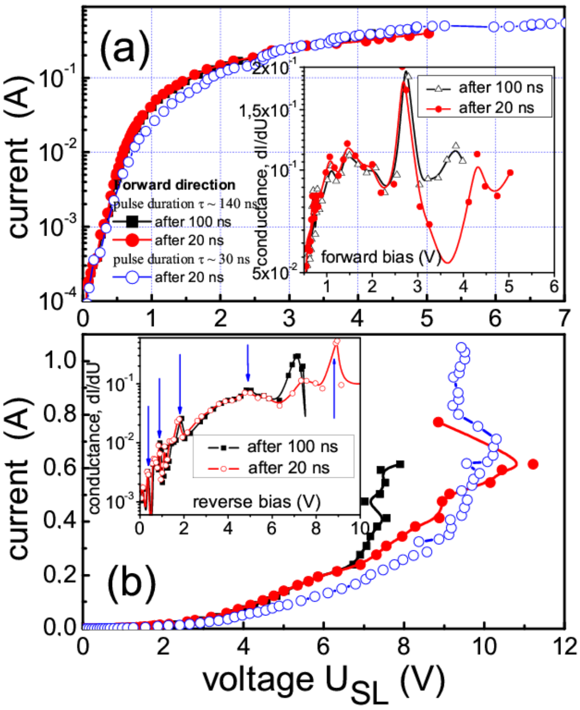

Fig. 3. Current–voltage characteristics under forward (a) and reversed (b) bias. Curves are recorded using pulses of 30 ns and 100 ns duration. Insets in (a) and (b) depict conductance under forward and reversed bias, respectively. Arrows indicate non- -equidistantly distributed spikes related to the sequential resonant tunneling.

will be discussed elsewhere as an indirect illustration of parametric microwave gain in the studied structure [10].

To summarize, the application of nanosecond pulsed technique is a powerful tool to study carrier transport nonlinearities in a strong electric field in silicon doped $GaAs/Al_{0.3}Ga_{0.7}As$ superlattices. The nanosecond time scale measurements allowed one to discriminate the Wannier–Stark states (the Esaki–Tsu regime) and sequential resonant tunneling effects in biased structure at room temperature.

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