Time-resolved electroluminescence spectroscopy of resonant tunneling in GaAs-AlAs superlattices

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The carrier transport through a resonantly coupled GaAs-AlAs superlattice is investigated by time-resolved electroluminescence. Ultrashort current pulses are used to electrically inject electrons and holes into an externally biased superlattice. The time evolution of the emitted light is recorded, which allows us to directly monitor the temporal development of the carrier transport *and* the associated dynamics of the electric field. At resonance a strong reduction of the initial rise time of the electroluminescence signal is observed. © *1996 American Institute of Physics.* [S0003-6951(96)01321-6]

Resonant carrier transport through GaAs-AlAs quantum well heterostructures has gained increasing attention in recent years due to the applicability of these devices for optical communication, high-frequency oscillators and high speed optical switches.[1] A number of investigations have been conducted in order to determine the switching speed of a resonant tunneling diode, which possesses potential applications as a fast optical switch or a high frequency optical modulator.[2,3] However, due to a lack of very fast current pulse generators, most of the investigations have been limited to a time resolution in the nanosecond regime.

In this letter, we present a new technique, which allows a temporal resolution on the order of tens of picoseconds. An extremely short current pulse is launched from an Auston switch,[4,5] which is triggered by a femtosecond light pulse. The electrical pulse simultaneously injects electrons and holes into the intrinsic region of a *p-i-n* diode. The subsequent recombination light is recorded using a time-resolving streak camera system. This new technique will therefore be referred to as time-resolved electroluminescence (TREL).

The investigated device is a GaAs-AlAs superlattice (SL) with 21 nm GaAs quantum wells separated by 2.5 nm AlAs barriers. The 40 period SL is embedded in the intrinsic part of a *p-i-n* diode with highly doped contact regions. Mesa structures with a diameter of 120 μm are realized using conventional optical lithography and wet etching techniques. The Auston switch is formed by a metal-semiconductor-metal (MSM) diode consisting of an interdigital finger gate of 10 gold fingers evaporated on low-temperature grown GaAs (LT-GaAs).[6] The RC-time constant of the Auston switch is estimated to be about 25 ps. The sample is mounted in series to the Auston switch on a high-frequency (HF) 50 Ω stripline, which is connected to impedance matched HF electrical connectors. The setup is attached to the cold finger of a continuous He-flow cryostat. All measurements are performed at 4.2 K. The dc-bias voltage is applied by a voltage source (Keithley SMU236) which also monitors the time-averaged current. The Auston switch is triggered using a pulsed Ti:sapphire laser tuned to 795 nm with a pulse width of 150 fs. Since the lifetime of the EL signal can be larger than 100 ns, the repetition rate of the laser is reduced by a pulse picker to 1.9 MHz. The emitted electroluminescence signal from the diode is focused onto the entrance slit of a 0.22 m monochromator (600 lines/mm grating). The dispersed light is recorded by a Hamamatsu streak camera (C5680) which exhibits a temporal resolution of 2 ps. The streak camera was operated in single-shot mode and triggered by the pulse picker. The images were recorded by a charge coupled device array. The overall time resolution is only limited by the duration of the electrial excitation pulse arriving at the sample, which is estimated to be about 25 ps.

Figure 1 shows three time-resolved EL spectra recorded at different applied voltages. The intensity of the EL signal is displayed using a grey scale. The recombination of electrons in the lowest conduction band C1 with holes in the highest valence band state H1 results in a luminescence signal at an energy of about $E_{C1H1}=1.525$ eV. When a bias is applied to the SL, the bound states of the quantum wells between adjacent wells are tuned in energy. If the energy of the applied electric field over one period eFd matches the energy splitting of the ground state C1 and an excited state Cn, $n=2,3,...$, resonant coupling between adjacent wells occurs.[7,8] In Fig. 1(a) the transient EL spectra below the first conduction band resonance C1C2 are shown (2.0 V). The signal increases in intensity over the whole time range of 80 ns. Due to the very long lifetime of the EL, a finite signal can even be seen at times before the switch is triggered. This EL signal originates from carriers injected into the device by closing the Auston switch with the proceeding laser pulse. For this voltage the EL lifetime exceeds the excitation pulse separation, which is about 250 ns. With increasing bias the maximum of the EL intensity shifts to shorter times. In Fig. 1(b) for an applied voltage of 3.5 V the EL signal peaks already 12 ns after the switch is closed. At even higher voltages of 5.5 V

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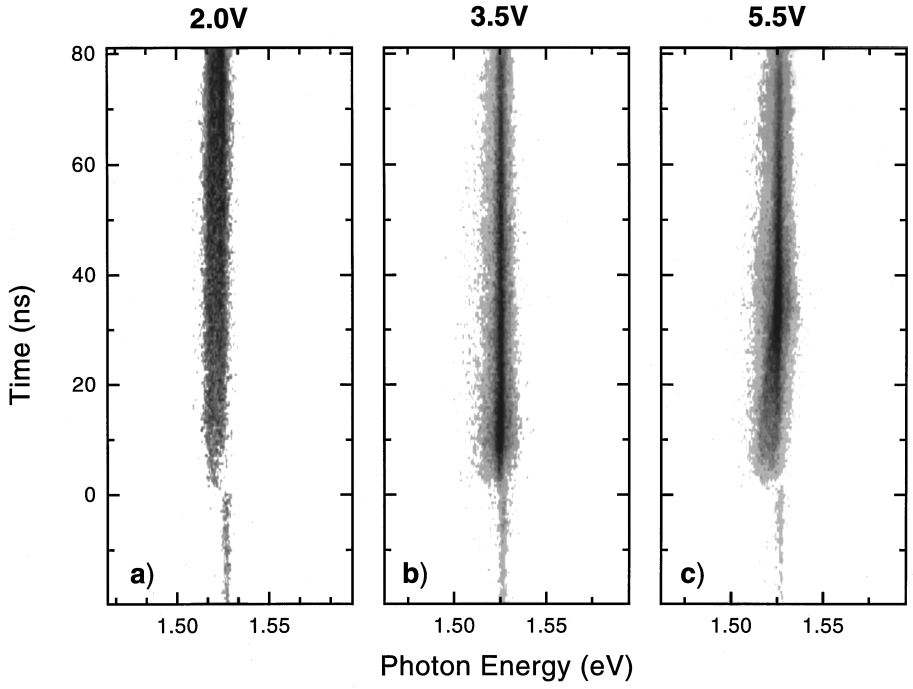

FIG. 1. Grey scale plots of the temporally and spectrally resolved electroluminescence signal for three different applied voltages: (a) 2.0 V, (b) 3.5 V, and (c) 5.5 V. The spectra are recorded at 4.2 K with a dc-bias applied to the Auston switch.

(cf. Fig. 1(c)) the maximum of the EL intensity again occurs at later times (35 ns). While the intensity gives information about the carrier transport, the spectral position of the EL line provides information about the electric field strength in the superlattice. Looking at Fig. 1 again, the EL emission at very short times (near 0 ns) is always shifted to lower energies compared to the spectra at very long times (essentially the remaining signal before the switch is closed again). This redshift originates from the Stark-effect of the electric field, which is created by the carriers injected via the electrical excitation pulse. Thus, with increasing time the electric field across the SL is reduced by tunneling and subsequent recombination of carriers. This reduction of the electric field is directly monitored by the increasing blueshift at longer times. For larger applied voltages (off resonance) this behavior is even more pronounced since the initially created field is higher and the carrier transport is slower thus resulting in a larger blueshift of the emission line at very long times, i.e. from the proceeding pulse.

The origin of the reduced rise time at 3.5 V is resonant tunneling from the C1-state of one quantum well (QW) into the second conduction subband of the adjacent QW. This resonant behavior can be clearly seen in Fig. 2, where the integrated intensity of the EL transition 10 ns after applying the bias is plotted versus the applied dc voltage. The voltage dependence of the EL intensity shows an onset at 2 V, which corresponds only to a small applied electric field, since the built-in voltage due to the highly doped contact regions amounts to approximately $V_{BI}=1.52$ V. With increasing applied voltage, the intensity exhibits a maximum at 3.5 V, which is slightly above the calculated conduction band resonance C1C2. The calculation was performed in the effective mass approximation by numerically solving Schrödinger's equation in the presence of a constant, homogeneous electric field for an isolated system of two QWs separated by a tunneling barrier of 2.5 nm width. For higher voltages the intensity first decreases followed by a strong increase with a second maximum at 8 V. This resonance is slightly above the calculated C1C3 resonance. The small difference between observed and calculated resonance voltages probably originates from a field screening by residual carriers at the contacts, which are still present until the next excitation pulse arrives. This interpretation is supported by the observation of a weak EL signal prior to the arriving laser pulse.

In order to analyze the transient behavior of the EL intensity, we have taken temporal streaks from the images, which are spectrally averaged over the recombination energy range of the C1H1 transition. The inset of Fig. 3 shows a comparison of two streaks for different bias voltages. The solid line corresponds to a streak recorded at the C1C2 resonance field strength, whereas the dashed line indicates a

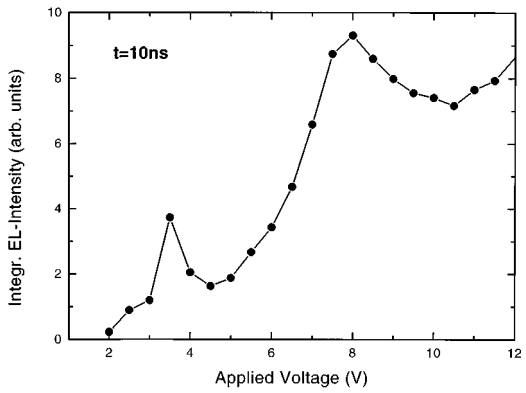

FIG. 2. Voltage dependence of the spectrally integrated EL intensity at 10 ns after triggering the Auston switch. Two resonances are clearly observed at 3.5 and 8.0 V.

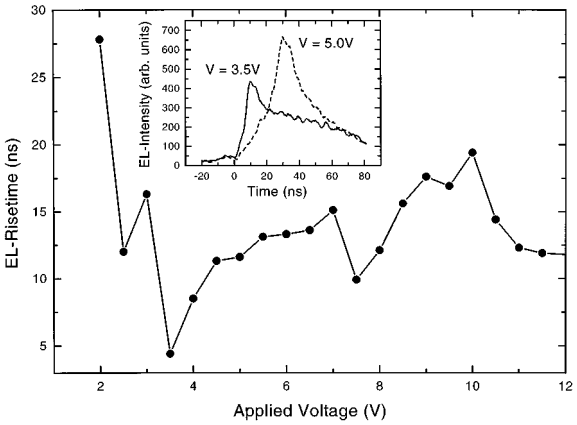

FIG. 3. Time-constants as obtained from the fit of the rise of the transient to a single exponential, versus applied bias. The time resolution is estimated to be below 25 ps. The resonant behavior at 3.5 V is obvious. The inset depicts transients at resonance 3.5 V (full line) and above resonance at 5.5 V (dotted line).

streak at a higher, off-resonance voltage. Both traces clearly show a rise and a subsequent decay of the EL signal. However, the resonant streak exhibits a much faster rise and decay compared to the nonresonant case. Due to the increasing time-integrated current with increasing electric field, the number of carriers and thus the total current pulse is larger at higher applied voltages. Therefore the intensity of the transient EL signal integrated over the whole time range also increases with increasing bias voltage.

By fitting the rise of the streaks for different values of applied bias to a single exponential we can deduce the rise time of the signal which is correlated to the transport time of electrons and holes. However, we have to state that at high fields the analysis of the transients is more complicated due to field inhomogeneities arising from transport of both electrons and holes. Moreover, due to the higher effective mass and thus reduced mobility of holes we expect the transport to be dominated by the electron motion through the superlattice. The EL rise time versus voltage is shown in Fig. 3 by full circles. The enhanced transport due to resonant coupling of the conduction band states is clearly resolved by a much faster rise of the signal at the C1C2 resonance voltage (3.5 V) and the C1C3 resonance (8.0 V). In the first case the average carrier transport time over a SL period is found to be 109 ps at resonance, compared to 407 ps for off-resonance, which is comparably slow. However, since the electric field across the intrinsic part is time-dependent the carrier transport will slow down with reduction of the applied field due to tunneling and recombination of carriers.

In summary, we have measured the first time-resolved electroluminescence spectra of resonantly coupled GaAs-AlAs superlattices. This technique, which is capable of a very high temporal resolution, allows one to directly monitor the carrier transport and the electric field dynamics in time. Clear evidence for resonant tunneling is observed resulting in a fast EL rise and decay at the resonant alignment of the C1 and C2 conduction band states in adjacent wells.

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