Surface acoustic wave-induced electroluminescence intensity oscillation in planar light-emitting devices

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Electroluminescence emission from surface acoustic wave-driven light-emitting diodes (SAWLEDs) is studied by means of time-resolved techniques. We show that the intensity of the SAW-induced electroluminescence is modulated at the SAW frequency (∼1 GHz), demonstrating electron injection into the p-type region synchronous with the SAW wavefronts.

Surface-acoustic-wave (SAW) based devices are nowadays widely used for mobile and wireless applications, as well as for satellite communications and military applications1. The large-scale diffusion of sophisticated communication systems stimulated a fast rise in the SAW-based device market, reaching a production volume of several million devices per day2. More recently SAWs have attracted the interest of the semiconductor community in view of the exploitation of their interaction properties with two-dimensional-electron-gases (2DEGs) embedded in semiconductor heterostructures3,4. SAWs propagating through mesas containing high-quality 2DEGs indeed drive modifications on the 2DEG equilibrium state. Acoustic waves propagating along piezo-electric substrates are accompanied by potential waves which can trap electrons in their minima and induce dc currents or voltages5,6,7. The discovery of the so-called acoustoelectric effect was followed by the proposal of innovative device concepts. Among these Talyanskii et al. proposed the implementation of a novel current standard, demonstrating very precise acoustoelectric current quantization due to charge drag by SAWs through a quantum point contact8,9,10,11,12. Control over the constriction width allows very precise selection of the number of electrons packed in each SAW minimum down to the single-electron-transport regime. One of the most appealing applications proposed after the first report of the acoustoelectric quantized current was to incorporate single-electron SAW pumps in planar 2D electron/2D hole gas (n-p) junctions to fabricate high-repetition-rate single-photon sources.

Very recently two different groups demonstrated one of the main building blocks of such source, that is the possibility to switch on the electroluminescence of planar n-p junctions by applying SAWs13,14. From a more fundamental physics point of view these results extend the acoustoelectric effects to planar systems where both electron and holes are present and allow detailed studies of the effects of the acoustic modulation in light-emitting devices (LEDs).

In this Letter we report on time-resolved studies of the acoustoelectric effects in planar LEDs. We fabricated devices containing lateral n-p junctions and interdigital transducers for SAW generation (SAWLEDs) and studied the optical properties of the devices induced by the acoustic perturbation. We monitored SAW-induced electroluminescence (EL) as a function of time and demonstrated the presence of oscillations with the same period of the SAW (∼1 ns).

Devices were fabricated starting with a p-type modulation-doped Al0.3Ga0.7As/GaAs heterostructure grown by molecular beam epitaxy, containing a two-dimensional hole gas (2DHG) within a 20-nm-wide GaAs quantum well embedded 70 nm below the surface. The measured hole density and mobility after illumination at 1.5 K were 2 × 1011 cm−2 and 35000 cm2/Vs, respectively.

The heterostructure was processed into mesas with an annealed p-type Au/Zn/Au (5/50/150 nm) Ohmic contact. The fabrication of the n-type region of the junction followed Ref. 15. The Be-doped layer was removed from part of the mesa by means of wet etching (48 s in H3PO4:H2O2:H2O = 3:1:50) and the sample was loaded into a thermal evaporator for the deposition of a self-aligned Ni/AuGe/Ni/Au (5/107/10/100 nm) n-type contact. After annealing, donors introduced by the n-type contact provide conduction electrons within the well thus creating an electron gas below the metal pad, adjacent to the 2DHG (inset of Fig 1(a)). The n-contact was shaped as a thin stripe placed perpendicular to the SAW propagation direction, 250 μm away from the p-contact.

SAWs propagating along the (011) crystal direction were generated by means of an interdigital transducer (IDT) composed of 100 pairs of 200 μm-long Al fingers with 3 μm periodicity (∼1 GHz resonance frequency on GaAs). Transducers were fabricated at a distance of...
800 µm from the mesa by electron-beam lithography. The width of the n-type contact stripe (2 µm) was chosen of the same order of magnitude as the SAW wavelength (3 µm) in order to limit SAW damping due to the massive metalization and SAW diffusion originating from non-uniform penetration of the Ohmic contact and inhomogeneities in the etched region.

Several SAWLEDs were fabricated and studied, and all of them showed qualitatively similar characteristics. All of the data shown in the following refer to one representative device, for which the transport and optical properties of the junction, as well as the efficiency of the transducer, will be systematically analyzed.

The SAWLED was first electrically tested at low temperature to verify the proper formation of the lateral diode. Current-voltage curves (IVs) at different temperatures (from room temperature down to 5 K) showed rectifying behavior and intersected at ∼1.5 V (see Fig. 1(a)). This value corresponds to the diode conduction threshold and it is consistent with the value expected for GaAs n-p junctions. Emission properties were characterized by EL measurements at low temperature (5 K). Spectra as a function of bias were collected by a cooled CCD after spectral filtering by a single-grating monochromator. The EL spectra reported in Fig. 1(b) show a main peak at 818.7 nm (full width half maximum (FWHM) of 1.8 nm) originating from radiative recombination within the QW and a secondary peak at 831.2 nm (FWHM 3.6 nm) which originates from carbon impurities included in the heterostructure material during growth [16]. The origin of such peaks was also verified by photo-luminescence measurements [17]. Light intensity, calculated by integration over the main EL peak from 810 nm to 826 nm, as a function of the forward bias applied to the junction reflects the rectifying behavior of the IV curves (inset of Fig. 1(b)), showing a detection threshold of ∼1.65 V.

The SAW resonance frequency was determined by measuring the power reflected by the transducer as a function of excitation frequency. The transducer frequency response displayed at 5 K a pronounced dip at 987.5 MHz, which is consistent with the periodicity of the transducer, and had a FWHM of 2.4 MHz.

The travelling electric field associated with SAWs can drive electrons into the 2DHG when the junction is biased just below threshold [13, 14]. Indeed, we observed the light versus voltage curve to shift to lower biases by ∼10 meV in presence of SAWs (Fig. 2(a)). The maximum shift was observed at -10 dBm power level. At higher levels the increased electron extraction is counterbalanced by the spatial separation of electrons and holes trapped respectively in SAW minima and maxima, leading to a progressive suppression of the EL signal [12].

The emission spectra were changed by the SAW only in intensity and no spectral shift of the main peaks was observed (Fig. 2(b)). Light-intensity data as a function of IDT excitation frequency demonstrate that emission intensification occurs only within the transducer passband, as shown in the inset of Fig. 2(b).

We also studied the SAW-induced EL signal by time-resolved measurements. To this end the EL signal was spectrally filtered by a triple grating monochromator and detected by a single-photon APD module (Perkin Elmer SPCM-AQR-16). In order to obtain time-resolved EL traces we used time-correlated photon-counting techniques. The signal from the SPCM was directed toward the START input of a Becker & Hickl SPC-600 computer board, while the STOP input was driven by a signal synchronous to that used to generate the SAW. A typical data trace is shown in Fig. 3(a). EL oscillations with period of about 1 ns are present in the curve, reflecting the presence of the SAW modulating the junction potential. These oscillations are more clearly visible in Fig. 3(c) where a magnified view of Fig. 3(a) is displayed with a smoothed data trace. This effect is further highlighted in the frequency domain of the signal. Fig. 3(b) reports the Fourier transform of the EL signal. A single peak at the SAW frequency clearly dominates the Fourier transform.

Time-correlated measurements were made at different biases applied to the junction. The oscillation amplitudes...
were calculated from the Fourier transforms and normalized by the corresponding mean EL intensities. In the inset of Fig. 3(b) we report the normalized oscillation intensity as a function of the forward bias. The oscillation amplitude is around 1.5% of the signal and remains almost unchanged at different bias voltages, as expected for an exponential increase of the EL close to the conduction threshold. Since the recombination time in our system is much less than 1 ns, determined by means of photoexcited-carrier lifetime measurements, the reason for the observed small oscillation amplitude originates from other limiting factors. Ideally the SAW wavefronts would get to the thin n-type contact without any distortion and perfectly parallel to the contact itself. But real devices introduce deviations from the picture described above. The presence of the mesa edges and of defects along the SAW path introduced during the mesa etching process constitute scattering centers which lead to modification of the acoustic wave-fronts. In addition, annealed Ohmic contacts have a strong corrugation. During the annealing process metal diffusion makes the junction edges irregular on the scale of the SAW wavelength. These two factors lead to electrons being extracted and recombining at different times depending on their position along the junction. The resulting oscillations are therefore averaged out, while the EL mean-intensity increase still remains present. We believe that further optimization of the device geometry will lead to high contrast oscillations and is currently being investigated.

In conclusion, we fabricated n-p lateral junctions with interdigital transducers and studied the effect of SAWs on the device time-resolved emission properties. SAW-induced emission was first characterized by spectral measurements and light-voltage measurements. Electroluminescence was observed to increase in intensity in the presence of SAWs when the diode was biased near the conduction threshold. Time-resolved measurements of the electroluminescence in the presence of SAWs were carried out at several bias voltages, demonstrating modulation of the light intensity at the frequency of the SAW (∼1 GHz). The amplitude of the oscillation was found to be ∼1.5% of the total light intensity, almost independent from the bias applied to the junction.

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