Novel optoelectronic signal processing via the combination of SAW and semiconductor heterostructures

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Abstract— The combination of surface acoustic waves (SAWs) and the superior electrical and optical properties of band-gap engineered semiconductor layer systems yields a completely new and promising approach toward another generation of acoustoelectric and optoelectronic devices. The propagating potential modulations accompanying a SAW on a piezoelectric semiconductor heterostructure can be exploited to alter the optical properties of an optoelectronic structure in many ways and over a wide range. We demonstrate the SAW-induced separation, storage and transport of photogenerated electron-hole pairs. Various schemes to release the carriers in form of a time delayed light signal are demonstrated and discussed. We present some basic structures and applications.

I. SAW and Optoelectronics

Electro-optic interactions based on excitonic processes are attracting more and more attention as they could provide new powerful mechanisms for generating, modulating and detecting optical signals and might play a keyrole in futures optoelectronic data networks. Todays band-gap engineering possibilities have reached a degree of refinement where almost any desirable set of optoelectronic properties can be tailored in a semiconductor heterostructure right from the drawing board. The study of the fundamental temporal and spatial carrier dynamics however is still a field of great interest. Especially promising seems to be the electric field driven modulation of a quantum wells optical properties. An increased understanding of the dynamic processes on a nanosecond and picosecond timescale is important for the improvement of lasers, modulators, detectors, all-optical switches etc. Strong interband optical transitions are seemingly linked to direct band-gap materials like GaAs. For some applications, however, it may be desirable to borrow characteristics of indirect semiconductors like the prolonged radiative decay time of electrons and holes. Former approaches tried to combine a direct band-gap in momentum space with an indirect gap in real space via band-gap engineering along the growth direction[1][2]. On a piezoelectric substrate a SAW is accompanied by strong vertical and lateral piezoelectric fields, creating a moving type-II potential superlattice within the quantum well plane, comparable to a lateral nipi-structure, in a very direct and elegant way. We summarize here some experiments on the reversible storage of light in form of spatially separated photogenerated electron-hole pairs in the dynamic potential superlattice of a SAW and point out possible applications. A crucial role in our experiments is played by the translation of photons into electron-hole pairs via interband-absorption at the optical input and the retranslation of electrons and holes into photons via radiative decay (photoluminescence, PL) at the optical output port. Energy relaxation of hot photogenerated carriers down to the band edges takes place on a ps timescale. Caused by their Coulomb interaction electrons and holes tend to form bound hydrogen-like systems, called excitons. As the typical excitonic binding energy in our quantum wells is about 10meV, they are easely ionized in the strong piezoelectric fields of a SAW. Similar experiments on the storage of light in form of separated electron-hole pairs were done for the potential landscapes induced by static interdigital transducer structures[3].

II. Typical device setup

We are presenting experiments on two different undoped InGaAs quantum well structures grown by MBE on semi-insulating (001)-GaAs substrate. Sample A is a single, 10nm wide $In_{0.15}Ga_{0.85}As$ quantum well, close to the surface (20nm GaAs cap-layer). Sample B consists of five 13nm wide $In_{0.2}Ga_{0.8}As$ wells, separated by 54nm thick GaAs barriers and additional 8nm GaAs as cap-layer. Interdigital transducers (IDT) are fabricated by electron-beam lithography, so that frequencies of up to 6GHz can be achieved. These transducer structures and therefore the SAW beam are aligned along the (110) direction. The cross-geometry shown in the inset in Fig. 1 al-

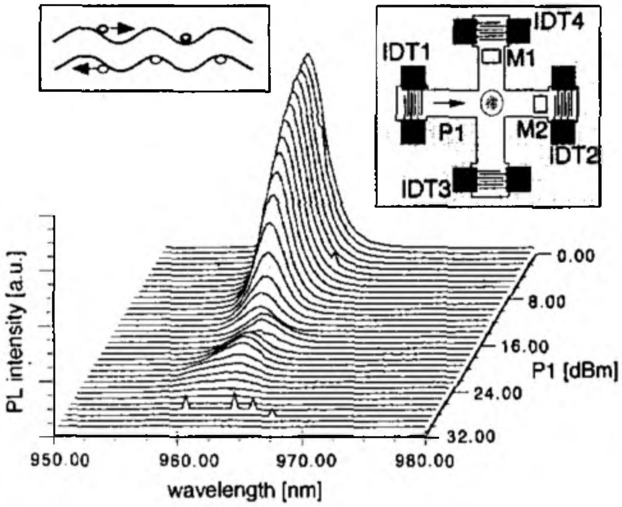

Fig. 1. Photoluminescence spectra on sample B at 5K for different acoustic powers. Electron-hole pairs are generated at the cross-center by a 780nm laser with an intensity of about $10mW/cm^2$. The insets schematically depict the sample design and the SAW field induced separation of the optically generated carriers.

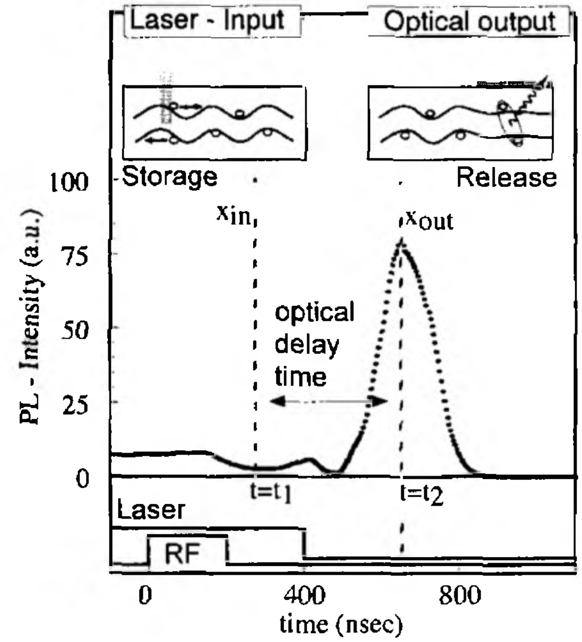

Fig. 2. Ambipolar transport of trapped charges on sample A at 5K [6]. At $t = 0$ a SAW pulse is launched from IDT1. Optically generated electron-hole-pairs at site x_{in} are separated and captured by the SAWs moving piezoelectric potentials. At site x_{out} the SAWs fields are deliberately screened by a semitransparent metallization, the transported carriers are released and recombine in a flash of light. The experiments timing is indicated in the lower part.

lows a variety of different experiments and the demonstration of the dominant acousto-electro-optical interactions all in one [4]. Typical transducer frequencies for our optical experiments are between 100MHz and 3GHz corresponding to wavelengths λ_{SAW} between $30\mu m$ and $1\mu m$. The insertion loss of the non-impedance-matched samples is typically about -8dB/transducer at 1GHz. Combined with a simple on-chip impedance matching network, we are able to reduce the insertion loss by a factor of two.

The samples are mounted in an optical cryostat and experiments were performed between 5K and 120K. The interdigital transducer frequency here is 890MHz and the optical signals are provided by a 780nm pulsed laser diode. The PL response of the sample was analyzed with a spectrometer and a liquid-nitrogen-cooled CCD camera.

III. The Photon-Conveyor-Belt

In Fig. 1 the direct PL response of sample B is shown under the influence of a SAW. The different PL traces are taken at T=5K for different acoustic power levels P_1. Clearly the PL strongly decreases with inceasing SAW amplitude until it is completely quenched. The quenching of the direct PL can be explained by field-ionization of the photogenerated excitons and subsequent separation of electrons and holes within the travelling potential superlattice like indicated in the inset in Fig. 1. Because of the drastic reduction of the wavefunction overlapp of electrons and holes the radiative recombination is almost completely suppressed. Photogenerated carriers in quantum well structures usually have a lifetime below $1ns$. By separation of electrons and holes within the SAWs piezoelectric fields, however, the lifetime is easely increased by several orders of magnitude. The carriers are captured within the moving superlattice, stored and transported across the sample until some mechanism is applied to release electrons and holes again. For intermediate acoustic powers of about 10-20dBm typical vertical and lateral fields are of the order $10^3 - 10^4 V/cm$. Even higher fields can be achieved on hybrid-systems, e.g. epitaxial-liftoff structures on $LiNbO_3$ [5]. To release the stored carriers, the lateral electric fields are deliberately screened by a semitransparent metallization at the end of the SAWs path. There electrons and holes will drift freely, quickly find each other and recombine in a flash of light.

Fig. 2 summarizes the whole process for sample A. At time $t = 0$ a SAW pulse is launched from the left transducer. As the pulse passes beneath the optical input port a light pulse charges the wave with electrons and holes. These carriers are then "surfing" separated and safely stored towards the optical output port where the SAWs potential modulation is screened by the thin metal film. The liberated electrons and holes are translated back into a light signal. Thus the initial light pulse is stored, delayed and transported for a rather long time as compared to the other time scales involved like the speed of light and the usual radiative recombination time of photogenerated carriers. During the runtime of the SAW additional signal processing may be applied to the light pulse represented by travelling electron-hole pairs. For example, the output light frequency can be shifted by additional vertical fields at the output port x_{out}, by scaling the well-width along the sample or by modifying the optical properties of the semiconductor by a lateral stressor structure at the samples surface.

IV. A OPTICAL FREQUENCY COMPARATOR

There are alternative ways for releasing the stored carriers and reassembling the initial light pulse. A very versatile method is to launch a second SAW pulse from the second transducer IDT2. The two pulses interfere and form a standing wave pattern if their frequencies and amplitudes are the same. Within the oscillating standing wave pattern electrons and holes periodically exchange their position because every potential maximum becomes a potential minimum after half a period and vice versa. As electrons and holes have to cross each others paths in this standing but oscillating potential superlattice, there will be an oscillating overlap of their wavefunctions inducing radiative recombination. Making use of this mechanism, the stored light pulse may be recalled from the sample by applying a second SAW of same frequency and amplitude. The position of the optical output port x_{out} is then adjusted by the temporal delay between the two pulses.

For the trace in Fig. 3 a), the amplitude of the first SAW pulse on sample A is adjusted to a point where the PL is quenched by about 50%. The horizontal axis shows the power level of a second counterpropagating SAW pulse. Obviously, the PL intensity is strongly increased when the amplitude of both waves is matched and a stable standing wave pattern is formed. If we rise the second SAWs amplitude further, the second pulse takes over the "surfing" carriers and again there will be complete quenching of the PL. Even more interesting is to use two SAWs of same amplitude but slightly differing frequency. A stable standing wave pattern can only be established if both frequencies are exactly the same, otherwise the resulting potential pattern will always be moving though at extremely low velocity. Fig. 3 b) shows the respective experiment. Astonishingly the frequency criterium has to be matched to an accuracy of $\Delta f/f \approx 10^{-7}$.

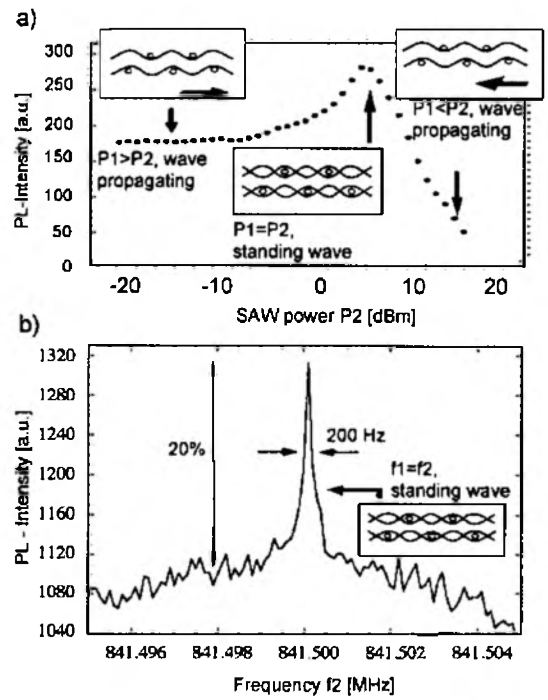

Fig. 3. Direct PL intensity (sample A) at cross-center for two counterpropagating SAWs with acoustic powers P_1 and P_2. a) P_2 sweep for constant amplitude P_1. For matched amplitudes the direct PL-intensity is significantly increased. b) Same acoustic powers $P_1 = P_2$ but slightly detuned frequencies. The PL shows a steep rise when frequencies are matched to an accuracy of 100Hz.

V. SPECIAL ISSUES FOR MULTILAYERED STRUCTURES

When considering realistic device structures it is important to investigate the interaction of a SAW with multilayered semiconductor structures as used for many optoelectronic applications (lasers, switches, modulators etc.). Here, we have to deal with systems of stacked quantum wells, quantum wells embedded in waveguide structures etc. These structures are extending far into the bulk and therefore the interaction with the piezoelectic fields of a SAW will get weaker. As a rule of thumb, the fields of a SAW are exponentially decaying into the bulk with a typical decay length of λ_{SAW} ($\approx 3\mu m$ in our experiments).

In layered structures the dynamic screening of the SAW fields by the field-generated free carriers might

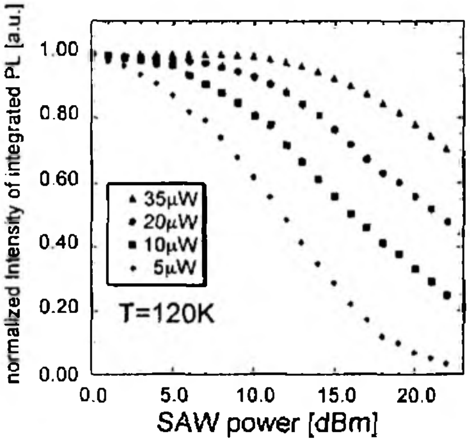

Fig. 4. Direct PL on sample B vs. acoustic power P_1 for different input laser intensities. For increasing laser intensities the screening by photocarriers becomes a dominant effect.

play a dominant role. As can already be observed for a single InGaAs surface quantum well the photogenerated, captured and separated electrons and holes build up an electic field opposite to the SAW-induced piezo-fields and therefore screen them. Thus, the SAWs capacity for transport will saturate with increasing carrier density. Obviously, this limit is more likely to be reached when quantum wells are stacked and the resulting screening of the SAW-fields adds up. Experiments on multi-well structures and structures with built-in optical wave guides clearly stress the importance of the mentioned points.

Fig. 4 shows a PL-quenching experiment on the InGaAs multi-well structure (sample B) for different optical intensities. We observe that for low laser intensities the PL is completely quenched as in the experiment discussed before, whereas for high intensities there remains a residual PL signal indicating the saturation regime. For the residual PL-signal a change in lineshape is observed at high acoustic powers, which is not observed for close-to-surface structures and might be explained by the depth dependence of the ratio between lateral and vertical piezo-fields.

VI. FUTURE PROSPECTS

We presented the basic mechanism of storing light in the form of electron and hole pairs, the bipolar carrier transport within the moving potential superlattice of a SAW and finally the reassambly of the initial light pulse. The translation of photons into long lived electron-hole pairs may serve as a general multi-purpose optical delay mechanism where additional signal processing can be performed to the light signal during its electron-hole metamorphosis. Modern fiber-optics data networks are still lacking a simple and efficient technology which would allow to directly route incoming light signals into a set of different output fiber channels without having to pipe them through the usual photodetector/electronic-circuitry/diode-laser assembly. We propose the application of a SAW-delay line structure as an optical router. The basic layout for such a device is already given in the inset of Fig. 1. Realized in this simple structure is an optical input and two optical output ports (metallizations M1 & M2). The switching between port M1 and M2 is done by a second SAW signal launched from IDT3 which takes over the carriers. Many of such new devices and applications might be thought of, once the crucial technological questions are solved. One of these questions concernes the effectiviness of room-temperature PL which of course is vital to the operation of our devices. It seems that PL in general is not weaker at room temperature than at low temperatures for impurity-free samples, where non-radiative decay processes are sufficiently suppressed. PL at 300K is of course spectrally broadened because of thermal broadening and interaction with phonons. The principal technical issues however are comparable to the questions arising in the design of LED structures which is a well developed field. Thus the development of optoelectronic devices, based on the interaction of optically generated carriers with SAW might advance just fast enough to fill in some of the missing links in optical signal processing.

VII. ACKNOWLEDGEMENT

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