Storage of photonic signals in semiconductor heterostructures

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Photonic signals are efficiently stored in semiconductor-based optical memory cells. The incident photons are efficiently converted into electron-hole pairs that are locally stored in a quantum well being laterally modulated by either static or dynamic tunable superlattices. At large superlattice amplitudes these spatially separated pairs can be held in the lateral superlattices for times many orders of magnitude longer than their natural lifetimes. At an arbitrary chosen time they can be released in a short and intense flash of incoherent light, triggered by flattening the superlattice amplitude.

The storage of optical photonic signals in a solid for memory applications and signal processing purposes is an interesting task in view of the constantly growing impact of optical communication technology. Basically, light can be transformed into either an excited state of the solid, where the re-emission in the form of flourescence is delayed or stretched out for some time given by the probability of the transition from the excited to the ground state. Also, more complicated schemes are possible, where the energy of the primary optical radiation is stored in a chemical reaction which then can be reversed again to emitt light at some later times. Technologically, these two concepts have been employed in either flourescent displays or by charging a battery using a solar cell.

Here, we would like to report on a new technique to store optical signals which allows for a deliberate release of the information in the form of light at some predetermined moment and even at a different location than the one where the light was incident in the first place. We make use of the fact that incoming photons can create electron-hole pairs in a semiconductor structure. The idea then is to spatially separate those carriers and hence to strongly reduce the probability for recombination. Lifting the spatial separation at some point finally induces radiative recombination, thus re-emitting the optical signal. Such spatial separation of photogenerated carriers is achieved by the definition of a laterally modulated potential landscape in the plane of a semiconductor quantum well (QW). Here, the motion of the carriers is already confined to the plane of the QW. The lateral potential leads to an additional confinement which in turn is responsible for the spatial charge separation. The samples used for our expriments are 'off-the-shelf' standard heterojunction QW of arbitrary thickness, mostly in the 10 nm range. The layered systems employed are, for example, GaAs for the barriers and InGaAs for the active QW material. Close to the layer of the QW a laterally modulated potential relief is created either by applying a gate bias to lithographically defined gate electrodes or probably even more versatile by launching a piezoactive surface acoustic wave (SAW) across the sample. In both cases, potential modulations with an amplitude of the order of 1 Volt are easily achievable. Incident photons create electron-hole pairs, which according to their respective charge will immediately drift into the potential minima in the conduction and valence band, respectively. Those minima are laterally one half period of the potential modulation apart. If this period is choosen such that the resulting electron and hole wavefunction overlap is neglible, about 1 μm in our case, the probability for radiative recombination is strongly supressed and the carriers are efficiently trapped in form of oppositely charged stripes of photogenerated electrons and holes. Apart form technical differences, the effect of the lateral potential modulation on the subband-structure of the QW is the same for SAW or a static interdigitated gate on to of the sample surface. Photogenerated carriers are trapped in the lateral potential minima where they reside for unusual long times as compared to their natural lifetime. In a direct gap semiconductor, these lifetimes range in the order of 1 ns, here, storage times of more then 30 μs have been achieved.

To release this 'stored' information in the form of secondary photons, one has to deliberately flatten out the lateral potential modulation. In the case of a static interdigitated grating, this is easiliy achieved by simply removing the potential difference to the gates by switching off the gate bias [1]. The lateral and moving potential modulation associated with piezoactive SAW can be cancelled out by either depositing a thin metal layer at some point in the sound path or by creating a standing wave using a counterpropagating wave [2]. In both cases the trapped carriers are free to move again in the plane of the well, eventually recombining to emit a photon.

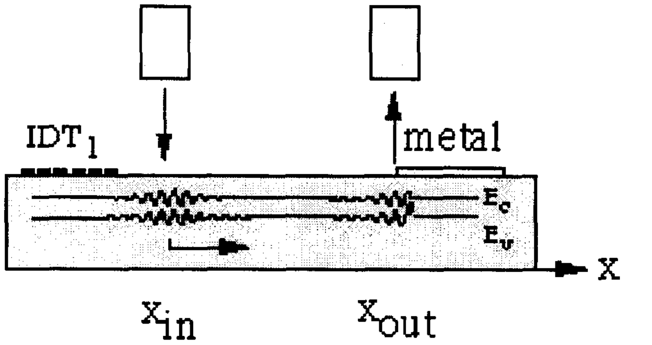

Fig. 1 : Schematic view of an optical delay line employing surface acoustic waves. Photogenerated carriers are trapped in the moving lateral potential of the SAW and can be released in the form of light by screening the piezoelectric field modulation.

In Fig. 1, we show the time delayed photoluminescence of a quantum well where light storage has been achieved in the field of a SAW. Here, the storage time is basically given by the length of the SAW path, at the end of which a thin metal film screens out the lateral potential propagating at the speed of sound [2]. When the wave reaches this metal film, the lateral piezoelectric fields that have been used to trap the photogenerated carriers are screened out and an intense time-delayed PL signal is detected at this location. The SAW frequency in this case was about 800 MHz, corresponding to a SAW length of about 3 μm.

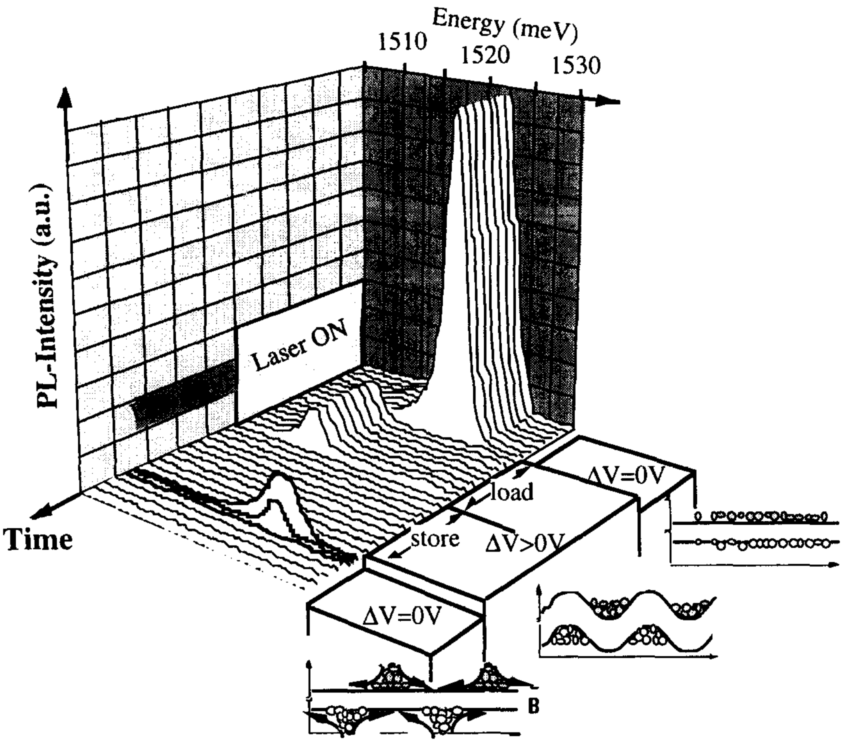

Fig. 2 : Time resolved measurement of the PL in an optical storage cell using static gate electrodes. During time (A), no lateral potential modulation is imposed on the quantum well. A sharp and bright PL is observed. (B) The lateral potential modulation is switched on and loaded with photogenerated carriers.(C) The laser is switched off while keeping the lateral potential modulation on. No PL is observed and the signal is stored in the structure. (D) Switching off the lateral potential modulation leads to the emission of a short and intense PL pulse.

In Fig. 2 we depict the result of an experiment, where statically defined interdigitated gated electrodes serve as the storage cell. Here, the charge can be held much longer as the lateral potential modulation is also static. After the storage time, the potential difference to the gates is set to zero, resulting in the emission of a short and intense PL flash. Even for storage times longer than 30 μs, no significant reduction of the intensity of the secondary light has been observed and much longer storage times are anticipated.

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[1] S. Zimmermann, A. Wixforth, J.P. Kotthaus, W. Wegscheider, and M. Bichler, submitted to Science
[2] C. Rocke, S. Zimmermann, A. Wixforth, J.P. Kotthaus, G. Böhm, and G. Weimann