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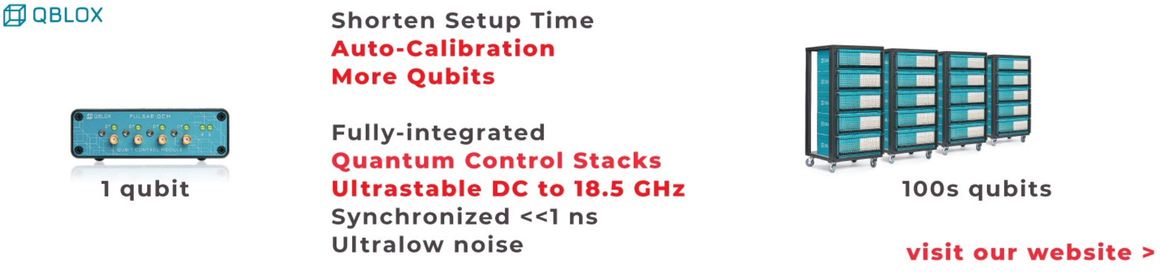

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Capture and release of photonic images in a quantum well

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The capture of an optical image in the plane of a semiconductor quantum well and the subsequent re-emission of this image in the form of a two-dimensional photon flux is demonstrated. Spatially resolved storage of photonic signals in a two-dimensional lateral potential landscape of the quantum well is employed to imprint optical images in the form of trapped photogenerated charges into the solid. The lateral two-dimensional potential modulation leads to very long storage times by a deliberate spatial separation of photogenerated electron–hole pairs. Once the potential modulation is lifted, the initial optical information is restored and the photographed image is released in a flash of light. © *2004 American Institute of Physics*. [DOI: 10.1063/1.1830676]

Recent advances in digital communication networks and optical interconnects also demand elaborate subsequent photonic signal processing. Storage, or more generally, the delay of optical signals and images is still a challenging task, especially for "last mile" applications.[1] For signals traveling at the speed of light, the use of conventional fiber delay lines requires path lengths in the kilometer range to achieve a delay of a few microseconds. Folded optical cavities or more exotic concepts like Anderson localization[2] do not easily allow for variable storage times and integration into existing networks. Recent developments on electromagnetically induced transparency in diluted gases or Bose–Einstein condensates offer interesting new possibilities, as in these systems the speed of light can be reduced by many orders of magnitude[3] or light pulses can even be halted,[4] allowing for much shorter delay paths. However, in spite of the impressive progress in this field over the last few years,[5] these methods still require considerable scientific effort to be technologically applicable.

A more promising approach to fill this gap is provided by photonic storage cells based on semiconductor materials. Several concepts of semiconductor-based optical and electro-optical storage devices have been developed 6–11. The latter rely on the attractive feature that in semiconductors with direct band gap such as GaAs or related III/V-materials, light is converted into spatially separated electron–hole pairs, which can be stored and converted back to light at will. Therefore, compact and comparatively cheap devices are possible. However, at the present state, they still suffer from limited storage time or slow response.

On the other hand, image recording by semiconductor charge coupled devices (CCD) is a well-established technique. However, they rely on serial, electronic readout.

Here, it is demonstrated that image recording and long-term storage combined with parallel, optical readout is possible, using an artificial three-dimensional potential modulation in a semiconductor quantum structure. We achieve a high density two-dimensional (2D) array of tunable pixels for the storage of photonic images in combination with fast optical readout and simple fabrication.

Based on the same physical principle to store light in the form of electronic excitations in a direct band gap semiconductor,[7–11] complete confinement of both photogenerated electrons and holes in three dimensions is achieved by different means for each direction (cf. Fig. 1). Confinement in the z-direction results from the use of a quantum well (QW) structure, a semiconductor layer sandwiched between material of higher band gap. In these systems, photons with energies above the band-edge of the QW material are absorbed and efficiently converted to electron–hole pairs, being confined in the QW layer. Without lateral confinement in the QW plane, the carriers immediately recombine radiatively on a nanosecond time scale.

In-plane confinement in one direction (y) is realized using a voltage-induced lateral potential superlattice: An interdigitated electrode at the surface of the semiconductor is used to provide a periodic potential modulation in the plane of the quantum well. The amplitude of the modulation is widely tunable by the voltages applied to the electrodes. For a sufficiently strong potential modulation, electron–hole pairs generated during illumination—are spatially separated. This considerably reduces the overlap of the wave functions, thus efficiently suppressing recombination. As long as the potential modulation is present, the carriers remain separated: Electrons and holes are accumulated in the plane of the quantum well beneath the positive and negative electrode, respectively. Turning the voltage off to remove the potential modulation enables the carriers to recombine radiatively, resulting in an intense flash of photoluminescence (PL). The operation principle could therefore be referred to as delayed

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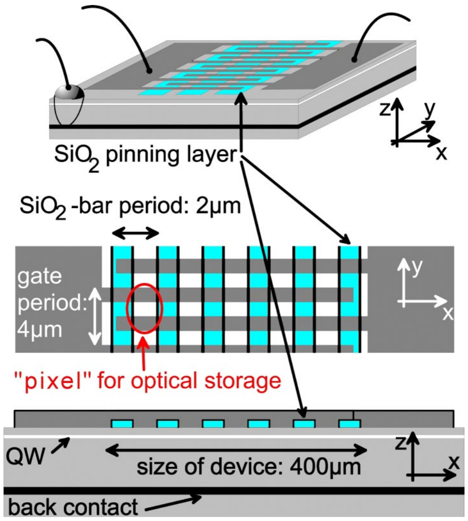

FIG. 1. Sketch of the device structure, also in top (center) and lateral view (bottom). The shape of the optical pixel is also indicated (picture not to scale).

PL with variable delay times, many orders of magnitude longer than those of intrinsic PL.[9]

Efficient electron–hole separation and confinement employing such interdigitated electrodes, however, is achieved only in the direction perpendicular to the electrode stripes. The unipolar charge plasma below each electrode stripe is still mobile along the parallel direction and will eventually occupy the whole structure by diffusion. This effect was studied in detail[12] and in fact turned out to constitute an almost perfect model system for two-dimensional spreading of charge.[13,14] However, this behavior is not suited for the storage of images, as a sharp optical image recorded by the cell would smear out during storage and its spatial information cannot be recovered in the output luminescence.

To achieve lateral confinement also in the *x* direction, we utilize the large density of surface states between the semiconductor and an oxide layer to prevent the penetration of the potential of the electrodes on top of the oxide stripes into the semiconductor beneath.

The structure is sketched in Fig. 1. The underlying semiconductor heterostructure is grown by molecular beam epitaxy and consists of a 20 nm Si-doped backcontact, which is contacted by alloying indium from the top. The rest of the structure is undoped and consists of a 1.5-μm-thick rear-barrier of $Al_{0.3}Ga_{0.7}As$, a 50 nm GaAs absorption layer with two 7-nm-wide $In_{0.11}Ga_{0.89}As$ quantum wells, a 150 nm $Al_{0.3}Ga_{0.7}As$ top layer, and a 5 nm GaAs cap layer. On top, an array of SiO_2 bars with both 1 μm width and spacing was deposited. Then, perpendicular to the oxide bars, the interdigitated structure was prepared; electrode width and spacing was again 1 μm. The total active area of the structure is 400 μm × 500 μm thus forming a 200 × 125 pixel array. Optical input was chosen at photon energies of 1.82 eV (680 nm), above the energy gap of the absorption layer but below the gap of the barriers.

Figure 2 demonstrates optical storage and readout of 2D spatial patterns. In (a) and (b), optical input is shown together with the optical output. As described above, devices providing only one-dimensional lateral confinement, do not conserve spatial information of the writing beam, cf. Fig. 2(a) lower left. The new devices presented here, however, provide high spatial resolution in the stored signal, cf. Fig. 2(a) lower right and Fig. 2(b).

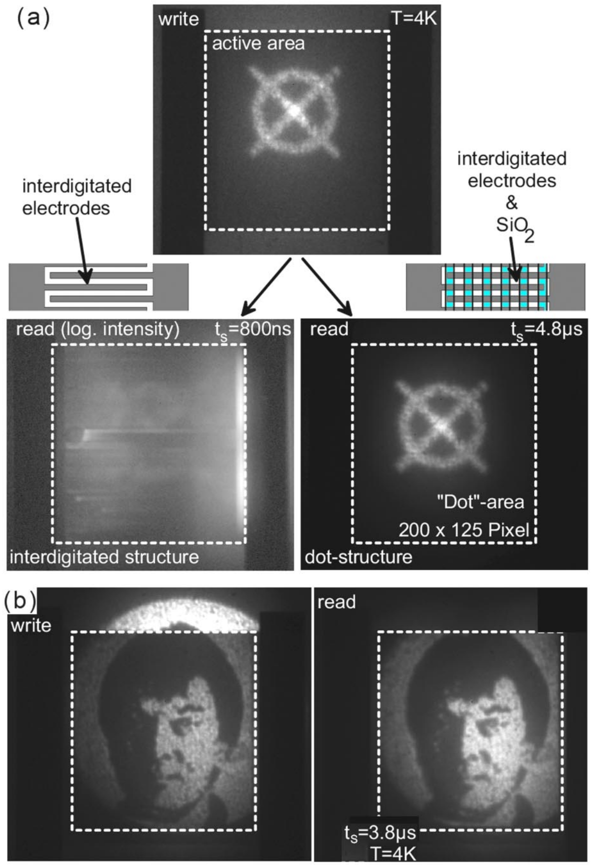

FIG. 2. Photonic imaging: stored optical pattern (top) and readout luminescence of a device without (a—bottom left), and with (a—bottom right), SiO_2 layer. In the left picture of (a), any spatial information is lost due to carrier diffusion along the electrodes, the luminescence is smeared out over the entire device. In the right part of (a), the spatial information is conserved by inhibiting carrier diffusion. In (b), the high image quality is demonstrated, using a photograph of a human face (left: PL during writing the image, right: delayed PL. Note that the illuminated area outside the pixel field while writing is not conserved in the readout picture.).

If a voltage difference is applied to the electrodes, the alternately positive and negative electrodes induce a sine-shaped potential modulation in the plane of the quantum well. Directly below the oxide bars, however, the modulation is altered. The resulting 2D potential landscape very much resembles an "egg box," with a grid of distinct potential minima for electrons and holes, respectively. If the structure is illuminated by the input pulse, the photogenerated electron–hole pairs are separated and confined to the nearest appropriate potential minimum. The spatial distribution of the optical signal is thus converted to a corresponding spatial distribution of electrons and holes stored in the QW plane. As the shape of the potential modulation does not allow for diffusion, the "latent carrier image" will not change with time. When the bias is removed to trigger the optical readout, carriers can recombine. As in GaAs the mobility of electrons exceeds that of holes by about one order of magnitude, the distribution of holes remains almost static while the electrons diffuse toward them, avoiding intermixing of the pixels.

In Fig. 3, an experiment is shown to prove the above-presented arguments. Using unusual high optical densities in the input pulse, the given potential modulation arising from

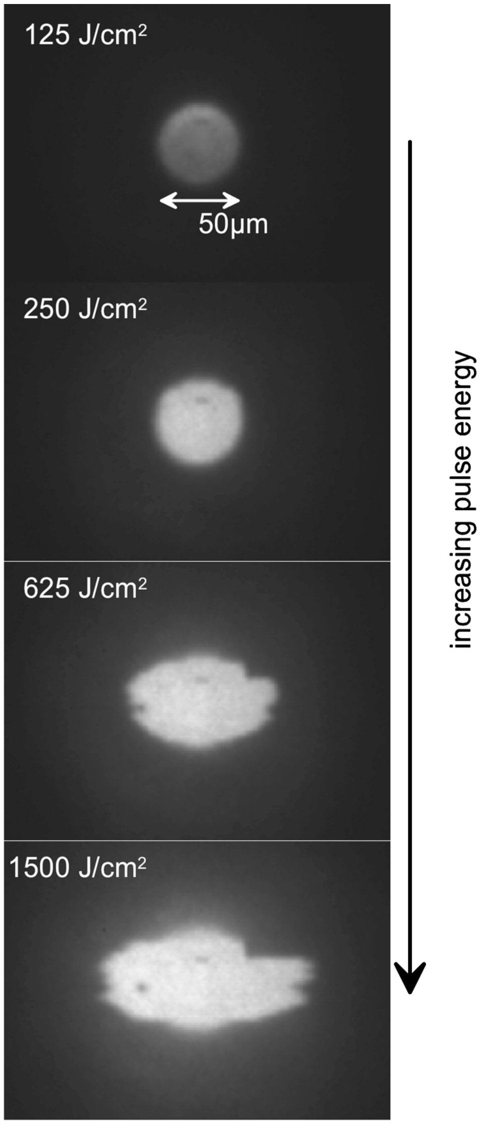

FIG. 3. Screening out the potential modulation of the interface states by photogenerated carriers: the given potential modulation induced by the electrodes is stronger than the potential modulation due to the surface states. The stored image of the round laser spot broadens along the electrodes.

the interface states is partially screened. The readout image is then smeared out along the metal electrodes.

It should be noted that by adding the patterned oxide layer, the readout time of the device can be considerably reduced. This is due to the fact that the diffusion of free carriers along the stripes is also reduced by the additional potential wells in the plane of the electron–hole system.

Despite the promising possibilities of the structures presented here, there are a few important restrictions to be addressed. First, all the experiments shown were performed at liquid-helium temperatures. However, voltage-controlled lateral potential storage cells have been demonstrated up to 100 K, using the (Al)GaAs material system.[9] In fact, not the lateral potential modulation, but the depth of the quantum well limits the operating temperature in these systems: Increasing temperature enables the stored carriers to thermally overcome the confining potential. The lateral potential modulation, can be tuned to several electron volts, sufficient for confinement even at room temperature. However, the depth of the quantum well is given by the semiconductor material used, ranging up to only a few hundreds of meV in the (Al)GaAs system. Here, the application of other materials, such as heterostructures based on ZnSe/MgS or InAlGaN may allow for substantial increase of the operation temperature.

The second point to discuss is quantum efficiency. Apart from thermal losses during storage, during storage, it is governed by three main processes: Absorption of the input light, fraction of radiative to nonradiative recombination (internal quantum efficiency), and extraction of the output light.[15] Absorption can be handled rather easily, e.g., by introducing specially designed absorption layers. The other two points are aspects shared by other optical devices based on III/V semiconductors, especially light-emitting diodes (LEDs): The internal quantum efficiency—especially at low temperatures—is usually very high in epitaxially grown structures, whereas the main bottleneck is the extraction of light from the semiconductor. Due to the high index of refraction of, e.g., GaAs, the angle of total internal reflection is very small. Over the last several years, this has been a subject of intense studies, resulting in elaborate structures for so-called “high-brightness-LEDs” (see, e.g., Ref. 16). In principle, these concepts can also be adopted in the devices presented here by appropriate structured QW barriers, which have a sufficient width for, e.g., the introduction of mirrors.

In summary, we demonstrated a semiconductor based opto-optical memory cell with adjustable storage times between nanoseconds and seconds allowing for the storage of complex optical patterns in combination with fast readout. The device is based on the conversion of light to electron–hole pairs and back to light. The generated carriers are stored in an artificial dot-like structure that can be tuned at will by external voltages. Complex images can be stored with very high quality, and readout times of 1 ns can be achieved in structures without back contact.

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