# Evidence of carrier confinement in nonlinear GaAs/AlGaAs multiple quantum-well microresonators fabricated using alloy mixing techniques

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Time-resolved photoluminescence measurements with $<5$ $\mu$m spatial resolution have provided direct evidence of carrier confinement in micrometer-dimensioned GaAs/AlGaAs multiple quantum-well microresonators delineated by alloy mixing. Carriers are confined in individual devices of size 2–50 $\mu$m without degradation of lifetime.

In a recent publication,[1] the fabrication of independent microresonators in a GaAs/AlGaAs multiple quantum-well (MQW) structure using an alloy-mixing technique was reported. Optical measurements under continuous wave laser excitation showed that a significant improvement of the nonlinear optical response was achieved through such pixellation. In this technique, shallow ion implantation and controlled thermal annealing induces alloy mixing in the surrounding MQW material, raising its band gap and lowering its refractive index. The aim of the pixellation is to add in-plane (transverse) carrier and optical confinement to that already provided in the normal (vertical) direction by the quantum-well barriers and the multilayer mirrors formed on either side of the MQW region. Such a structure is of considerable value when constructing two-dimensional arrays of all-optical logic gates or surface-emitting microlasers. In both cases, it is important that excess carriers—either optically excited or injected into the junction—remain within the active region rather than diffusing transversely and diluting their effect. For example, within a microlaser, the injection current must be confined in order to achieve high carrier densities at low current. Similarly, for the bistable optical logic gates discussed in Ref. 1, the condition for minimizing the switch energy corresponds to retaining all the photoexcited carriers within the smallest possible illumination spot area to maximize the subsequent changes in refractive index.

In both cases, it is essential that the pixel structure not only prevents transverse diffusion of free-carriers but also avoids enhancing electron-hole recombination rates. In the microlaser device, faster nonradiative recombination raises the threshold currents, while in all-optical logic gates the quasi-cw (equilibrium) carrier densities are reduced, and hence, the optical power levels required for switching are increased. Two approaches to providing carrier and optical confinement can be identified: (i) the alloy-mixing technique, referred to above, or (ii) the deep etching of mesa structures. The latter technique has been observed to significantly reduce carrier lifetimes as a result of surface recombination processes, both in nonlinear optical etalons[2] and in microlasers.[3] Alloy mixing, on the other hand, appears to avoid excessive recombination, as illustrated by low power optical bistability in nonlinear etalons.[1] In this letter, we report on an examination of the confinement of carriers at room temperature in GaAs/AlGaAs MQW pixels delineated by alloy mixing, using picosecond time-resolved photoluminescence (TRPL) techniques. The TRPL analysis was performed at high spatial resolution ($<5$ $\mu$m) on individual square pixels of lengths 5 to 50 $\mu$m. In addition, large-area TRPL analysis of a 2 $\mu$m pixel array is presented.

The sample was grown by metalorganic chemical vapor deposition (MOCVD),[1] and consisted of a back mirror (14 quarter-wave pairs of $AlAs/Al_{0.1}Ga_{0.9}As$, centered at 850 nm) and a MQW spacer consisting of 130 GaAs wells, 100 Å thick, each separated by 100 Å $Al_{0.3}Ga_{0.7}As$ barriers. It is comprised of arrays of square pixels of sides 2, 5, 10, 20, and 50 $\mu$m realized by shallow ion implantation followed by thermal annealing. The front mirror, not essential for the present experiment, was a $SiO_2/Si$ multilayer reflector.

The technique of time-resolved photoluminescence has previously been used to determine carrier lifetimes in bulk[4] and quantum-well[5–8] semiconductor material. The instrument employed in this study (based on an Edinburgh Instruments PL$\mu$S-2) is constructed around a microscope[9,10] and utilizes a picosecond laser diode excitation source and an actively quenched silicon single photon avalanche diode (SPAD) detector.[11] It exploits the time-correlated single photon counting technique and is capable of an instrument full-width-at-half-maximum (FWHM) of 50 ps. With reconvolution analysis, decays as short as 10 ps have been measured using this detection system. Because of the small size of the SPAD (5 $\mu$m diam), imaging from the sample plane to the detector can result in a spatial resolution of $<5$ $\mu$m. This instrument exhibits a combination of sensitivity, temporal resolution, and spatial resolution, which makes it ideal for the analysis of semiconductor microstructures.

The room-temperature photoluminescence (PL) decays from each of the pixel sizes between 5 and 50 $\mu$m are shown in Fig. 1. The sample excitation was provided by a laser diode operating at a wavelength of 776 nm, with a

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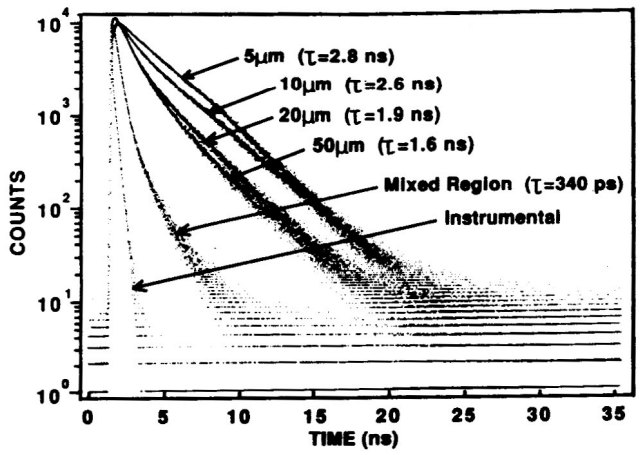


FIG. 1. PL decays from a GaAs/AlGaAs MQW microresonator structure, pixellated using alloy-mixing techniques. The sample was excited by 50 ps pulses, of energy 0.16 pJ and wavelength 776 nm, focused to a 3 $\mu$m diameter spot on the sample surface. The figure shows the PL decay detected at 840 nm for various pixel sizes between 5 and 50 $\mu$m. The estimated peak carrier densities generated are $\sim 5\times 10^{16}$ cm$^{-3}$. The PL decay from the mixed region detected at 800 nm and an instrumental response are also shown for comparison.

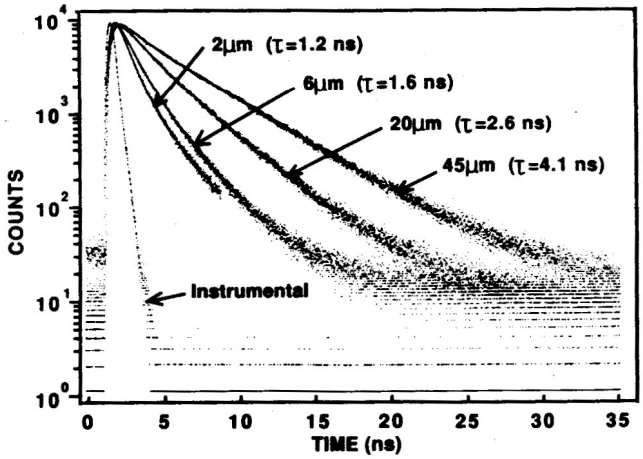


FIG. 2. PL decays from a 50 $\mu$m GaAs/AlGaAs MQW microresonator structure. Excitation was provided by 600 ps pulses at 776 nm, and the PL was detected at 840 nm. The different decays are of the sample emission for various excitation spot sizes between 2 and 45 $\mu$m diameter, at the same peak energy density of $\sim 125$ nJ cm$^{-2}$. The peak carrier density in this case was $\sim 2.5\times 10^{15}$ cm$^{-3}$.

repetition rate of 10 MHz, a pulse width of $\sim 30$ ps (FWHM), and a peak power of $\sim 5$ mW. The excitation radiation was focused to a 3 $\mu$m diameter spot on the sample, with a pulse energy density of 2.5 $\mu$J cm$^{-2}$—generating a peak carrier density of $5\times 10^{16}$ cm$^{-3}$. The imaging optics chosen resulted in a detected field of view of $\sim 3.5$ $\mu$m diam. The figure shows the PL decays for the different pixel sizes, where the luminescence detected was in the region 835–845 nm, corresponding to the peak of the PL emission spectrum. Also included is the instrumental response (i.e., the directly recorded excitation pulse) and the PL decay from the mixed region between pixels, detected at 795–805 nm (near its peak luminescence emission). It is immediately apparent that the PL lifetime is much reduced within the disordered region compared to that observed in the center of the largest pixels. Significantly, as the pixel size was reduced—thus bringing the surrounding disordered region closer to the 3 $\mu$m diameter excited area—the PL lifetime increased rather than decreased. This result is consistent with diffusion playing a significant part in the observed PL decay in the case of the larger pixels, while in the smaller pixels the excited carriers are being successfully confined within the $\sim 3.5$ $\mu$m diam area being monitored. For the smallest pixel (5 $\mu$m), the decay is close to a single-exponential with a time constant of $\tau = 2.8$ ns. Thus, in spite of the short lifetime observed in the disordered region, nonradiative recombination that might occur at the interface between the MQW and disordered regions appears to be negligible.

To determine the role of carrier diffusion further, the effect of increasing the excitation area was investigated. By illuminating a larger area, the reduction in the central carrier density resulting from diffusion is lessened, thus isolating recombination as the dominant mechanism determining the PL decay dynamics. Using the same detection field as before (i.e., $\sim 3.5$ $\mu$m diam), the PL decays from a 50 $\mu$m pixel were recorded for excitation spot sizes of 2, 6, 20, and 45 $\mu$m, as shown in Fig. 2. To remove any of the expected differences in decay rate associated with carrier-density dependent effects, the peak carrier density was maintained constant—at $\sim 2.5\times 10^{15}$ cm$^{-3}$—by increasing the excitation pulse energy as the spot size was increased. This necessitated an increase in the laser pulse length to 600 ps in order to provide enough energy to keep a constant 125 nJ cm$^{-2}$. It can be seen from Fig. 2 that the PL lifetime does indeed lengthen as the excitation area is increased, while the decay changes from multi-exponential towards a single exponential function. For the largest spot size (45 $\mu$m), the dominant decay time constant is 4.1 ns; implying that the $\tau = 2.5$–4.5 ns decays observed for the 5 $\mu$m pixels with 2–3 $\mu$m excitation spots (see Figs. 1 and 4) are the result of strongly inhibited transverse diffusion. Thus, it would appear that the mixed region forms a potential barrier around each pixel sufficient to confine the excess carriers well within the pixel—i.e., without exposing them to its own rapid recombination channels.

The smallest pixels fabricated were 2 $\mu$m squares. These proved to be difficult to assess individually (due to their small size) and so a different approach was used to study their TRPL response. In this case, both the excitation spot and the detection field of view were increased to $\sim 15$ $\mu$m diam. As the 2 $\mu$m pixels were configured in a square array with 5 $\mu$m pitch, this corresponded to observing $\sim 9$ pixels simultaneously and avoided the need for precise alignment. By again detecting only PL in the region of the MQW exciton absorption peak (i.e., 835–845 nm), it was possible to monitor the relaxation of carriers within the pixels while discriminating against the PL emission from the band gap-shifted mixed region, which, in any case, exhibited a much lower luminescence efficiency. Note that any carrier diffusion out of the pixels would only contribute to the mixed-region emission. Assuming diffusion of carriers into the pixel is negligible due to their short

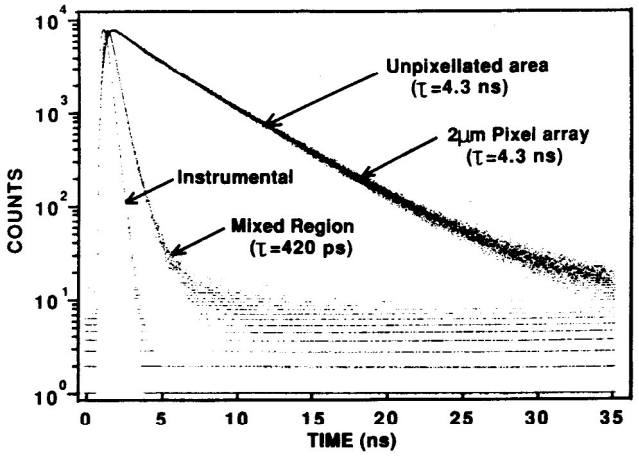


FIG. 3. Large area PL decays from an array of 2 $\mu$m microresonator structures, an unpixellated area, and a mixed region of the same sample. Excitation was provided by 600 ps pulses at 776 nm and the PL was detected at 840 nm for the array and the unpixellated region, and 800 nm for the mixed region. The excitation spot was $\sim 10$ $\mu$m in diameter and located in the center of the 20 $\mu$m diam detection region. The excitation pulse energy was 1.6 pJ. Note the complete overlap of the decays from the pixellated and unpixellated regions.

lifetime in the disordered material, then the response is equivalent to that for a singly excited pixel. To ensure sufficient excitation densities, the longer duration (600 ps), higher energy laser pulses were again used. The resulting PL decay is shown in Fig. 3 along with, for comparison, decays corresponding to the center of large (several mm$^2$) nonpixellated mixed and unmixed areas. It is apparent that the PL lifetime for the 2 $\mu$m pixels is the same as for the original material ($\tau$=4.3 ns), and hence, it can be concluded that, as with the larger pixels, carriers can be confined within the 2 $\mu$m pixels without degradation of their lifetime. For comparison, the PL decay of the disordered region has a time constant of only 300–500 ps.

Additional measurements of the PL decays obtained when the 5 $\mu$m pixels were excited with increasing pulse energy indicate a weak dependence of the dominant decay time constant on the initial carrier density. This is demonstrated in Fig. 4, where the decay time constant is plotted as a function of the excitation energy density, scaled to the pixel area. (It is assumed that rapid transverse diffusion within the 5 $\mu$m pixels increases the effective area from that of the initial 3 $\mu$m illumination spot.) Figure 4 also shows consistency between this set of results and the other comparable measurements on the 2 and 5 $\mu$m pixels, described above. The slower PL decays obtained at higher pulse energies suggest that a nonradiative (mono-molecular) recombination mechanism remains dominant as the excitation density is increased but that the finite density of traps and/or recombination centers impose a rate limitation on the relaxation process, as described by Fouquet *et al.*[6–8] Pickin and David[12] suggest that interfaces in the quantum-well structure provide the necessary density of flaws for single-exponential recombination to occur up to moderate

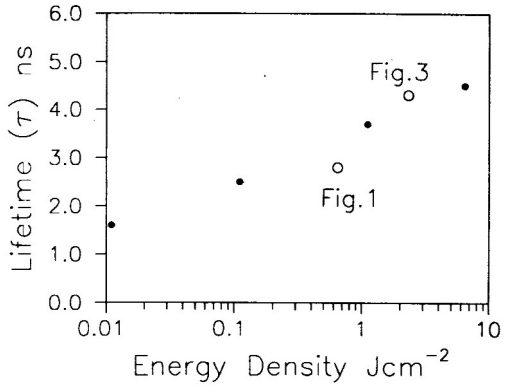


FIG. 4. The lifetimes deduced from single-exponential fits to PL decays for varying optical energy densities incident on a 5 $\mu$m pixel are shown (black dots). The incident energies used were 1.6, 0.29, 0.034, and 0.006 pJ/pulse which corresponds to carrier densities of $1.2\times10^{17}$ cm$^{-3}$, $1.7\times10^{16}$ cm$^{-3}$, $2.1\times10^{15}$ cm$^{-3}$, and $2.1\times10^{14}$ cm$^{-3}$, respectively, when scaled to the pixel area. Results obtained for the 5 $\mu$m pixel of Fig. 1 and the 2 $\mu$m pixels of Fig. 3 are shown for comparison (open circles).

carrier densities,[5–8] but again predict slower recombination at higher densities.

To summarize, we have observed evidence of carrier confinement in micrometer-dimensioned pixels of GaAs/AlGaAs multiple quantum-well material formed by the alloy-mixing technique. This confinement has been observed in square pixels as small as $2\times2$ $\mu$m$^2$. Carrier confinement in these pixellated structures will mean enhanced device performance for optically nonlinear microresonators and surface emitting lasers.

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