

# Nanostructures for long photoelectron lifetime

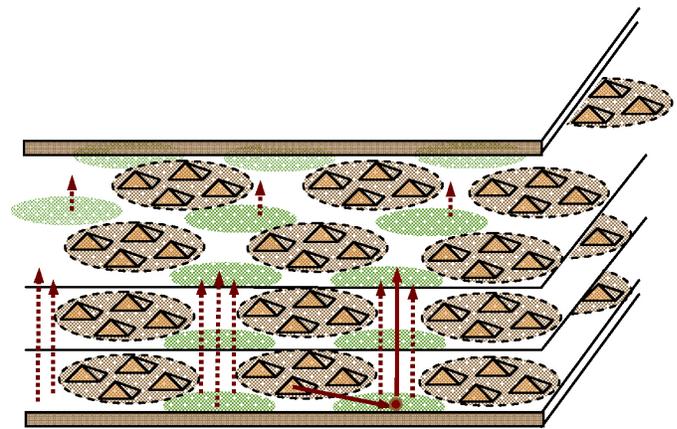
Andrei Sergeev, Vladimir Mitin, and Gottfried Strasser

*Carefully positioned potential barriers suppress photocarrier capture by quantum dots.*

Many optoelectronic devices are based on the phenomenon of photoconductivity, in which a material becomes more electrically conductive due to photocarriers (electrons and holes) created by electromagnetic radiation. Photocarriers contribute to the electric current until they recombine or are trapped by impurities and defects. Long photocarrier lifetime would substantially improve semiconductor devices, such as solar cells and infrared sensors. Various imaging devices working at liquid nitrogen temperatures use quantum-well infrared photodetectors (QWIPs) in an effort to extend photocarrier lifetime. At 77K, modern QWIPs operating at a wavelength of around  $10\mu\text{m}$  attain a detectivity of  $10^{10}\text{cmHz}^{1/2}\text{W}^{-1}$ , but this drops by two orders of magnitude at room temperature because of a tremendous decrease in lifetime. New nanostructured materials that provide long photocarrier lifetime at room temperatures would significantly increase the commercial market for infrared detectors and find numerous applications in public safety, industry, and healthcare.

Long lifetime improves responsivity and sensitivity of detectors and increases the efficiency of solar cells. Until recently, quantum dot (QD) nanostructures were considered a promising candidate for improving optoelectronic devices. These expectations were based on the concept of the 'phonon bottleneck,' which assumes that electron transitions are prohibited unless the difference between two discrete electron energy levels matches the phonon energy (a quantum of vibrational energy).

However, experiments have shown the complete opposite.<sup>1</sup> In reality, strong coupling between electrons and longitudinal optical phonons leads to the formation of polarons, quasiparticles that result when an electron in the conduction band of a semiconductor polarizes the lattice surrounding it. Polarons decay due to the interaction with optical and acoustical phonons. Slow (nanosecond) relaxation between electron levels has been

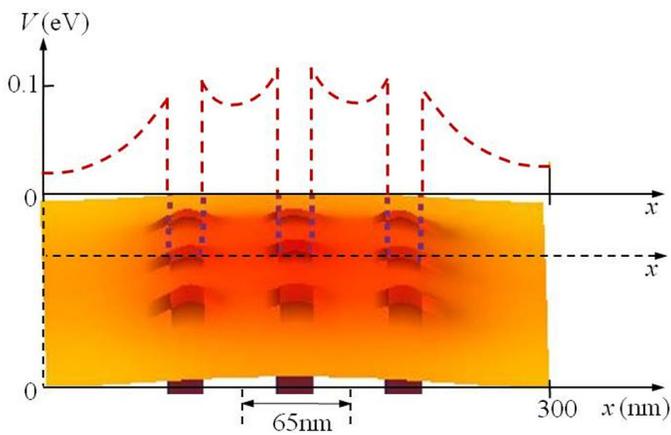


**Figure 1.** Structures with vertically correlated dot clusters. Quantum dots are represented by pyramids and dot clusters by gray areas, which are separated from the conducting channels (green areas) for the electric current (red arrows) by potential barriers.

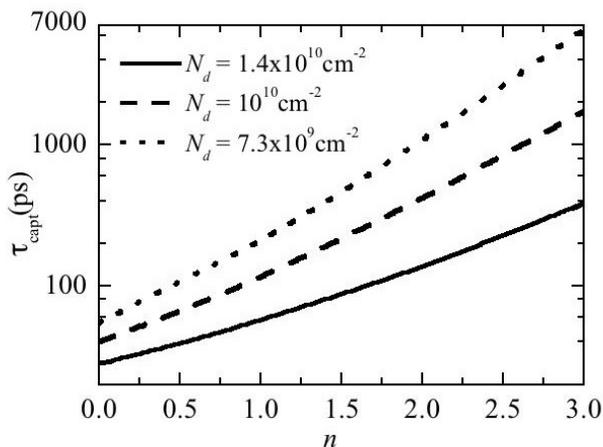
observed only at helium temperatures.<sup>1</sup> At room temperatures the polaron decay time is in the range of 2–30ps, which is too fast for the responsivity and sensitivity required for optoelectronic devices.

We have proposed a novel approach for controlling photoelectron lifetime based on suppression of photoelectron capture into the dots by means of potential barriers in specially engineered structures.<sup>2</sup> Figure 1 shows such a structure of vertically correlated dot clusters (VCDC). In these VCDC structures, a substantial barrier around a QD cluster is created by charged dots in the cluster. The QD clusters' positions are correlated in the direction of the electric current (vertically), and the barriers separate the conducting electron states in the matrix from the localized QD states. Having been excited by radiation, photoelectrons move in the areas between dot clusters via highly conducting channels, as shown by the red arrows in Figure 1. The potential barrier around a typical cluster with nine QDs is presented in Figure 2.

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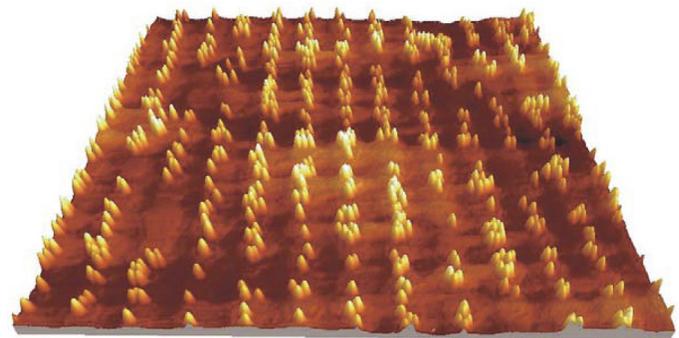


**Figure 2.** Band diagram of the vertically correlated dot clusters structure, showing the potential barrier around the cluster (red shows higher energy, yellow is used for lower energy). The red dashed line shows the potential barriers in a cross-section of the cluster. The distance between dots is 65nm and the diameter of the cluster is 300nm.



**Figure 3.** Capture time ( $\tau_{\text{capt}}$ ) as a function of dot occupation,  $n$ , for three values of quantum dot density,  $N_d$ .

We used Monte-Carlo modeling to demonstrate that the capture time increases exponentially with the number of dots in a cluster as well as with the average number of electrons localized in a dot or ‘dot occupation’  $n$ . Figure 3 plots capture time  $\tau_{\text{capt}}$  versus dot occupation for different dot densities in QD planes,  $N_d$ . In each case, the number of dots per cluster  $N$  is 9. Compared with ordinary QD structures, where the photoelectron lifetime at room temperature is of the order of 10ps, the VCDC structures with potential barriers created by charged dot clusters allow the photoelectron lifetime at room temperature to be increased by two to three orders of magnitude.



**Figure 4.** Atomic force microscope scan of InAs quantum dots grown on a patterned substrate with a period of 230nm.<sup>3</sup>

The VCDC structures can be fabricated by various methods. We have already seen promising results growing nanostructures on patterned substrates.<sup>3</sup> The patterning profile, etch depth of the pattern, and growth parameters of the epitaxial layer structure can control the clustering of QDs. Figure 4 shows an atomic force microscope scan of a patterned substrate with a period of 230nm overgrown with 20nm indium gallium arsenide ( $\text{In}_{0.2}\text{Ga}_{0.8}\text{As}$ ), 10nm gallium arsenide (GaAs), and 0.495nm indium arsenide (InAs). The dots align with the pattern of preferential nucleation spots created by the template and the InGaAs layer. Different QD alignments, from single QD ordering to clustering of QD arrays, allow us to fabricate different pattern sizes and profiles.

The VCDC structures have a set of characteristics making them especially suitable for optoelectronic applications. They have manageable photoelectron kinetics, which allows the carrier lifetime to be tuned to the values required by applications. Good control of QD levels and their occupations results in tunable highly-selective coupling to electromagnetic radiation, and they show high photoconductive gain and responsivity. In addition, they benefit from low generation-recombination noise due to low concentrations of thermo-excited carriers. High scalability of nanoblocks gives numerous possibilities for nanoengineering, and they can be manufactured using available technologies that are compatible with mainstream semiconductor manufacturing.

Our work suggests that QD structures with correlated clusters provide many possibilities for engineering of electron states. They have a strong potential to overcome the limitations of traditional QD structures for various optoelectronic applications. Our next steps will be to optimize the growth of clustered dot

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structures on pre-patterned semiconductors. Patterned surfaces with various pattern sizes and ratios of clusters versus non-cluster areas will serve as templates to grow the correlated clusters. Stacking QD layers on top of each other and embedding the total stack in contact layers will form vertically-clustered QD detectors. We will also optimize the operating regimes of novel detectors.

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#### Author Information

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