AIP Applied Physics Letters

The quantum dot spectrometer

J. L. Jimenez, L. R. C. Fonseca, D. J. Brady, J. P. Leburton, D. E. Wohlert et al.

Citation: Appl. Phys. Lett. **71**, 3558 (1997); doi: 10.1063/1.120390
View online: http://dx.doi.org/10.1063/1.120390
View Table of Contents: http://apl.aip.org/resource/1/APPLAB/v71/i24
Published by the American Institute of Physics.

The quantum dot spectrometer

J. L. Jimenez,[a] L. R. C. Fonseca, D. J. Brady, and J. P. Leburton
Beckman Institute for Advanced Science and Technology, University of Illinois at Urbana-Champaign, Urbana, Illinois 61801

D. E. Wohlert and K. Y. Cheng
Department of Electrical Engineering, University of Illinois at Urbana-Champaign, Urbana, Illinois 61801

(Received 15 September 1997; accepted for publication 14 October 1997)

We propose a novel photodetector capable of multi-spectral channel operation. The device makes use of the ability of a quantum dot plane to capture an optical spectrum, and of a resonant-tunneling structure to perform spectrally sensitive read-out. We present a design made out in the InAs–GaAs–$Al_xGa_{1-x}As$ system. We also present realistic simulations of the optical channel capabilities, as well as a discussion of the possible problems of the device. © *1997 American Institute of Physics.* [S0003-6951(97)02850-7]

Spectrally sensitive detection is inhibited in conventional semiconductor photodetectors because the scattering of the photoexcited carriers is much faster than the time required to collect the carriers at the device electrodes. The scheme of detection used is, therefore, based on the presence or absence of photoexcited carriers but disregards the energy at which these carriers are generated. This detection scheme is the only one possible in detectors which rely on photoabsorption to continuous energy bands because in excited bands phonon scattering is energetically allowed and is fast, thus washing out all the spectral information stored in the carrier energy.

To increase the detection capabilities of photodetectors, researchers have relied on optical filters such as waveguide demultiplexers or Bragg reflectors. However, these technologies yield only modest bandwidth resolution and spectral coverage, are expensive and difficult to integrate into arrays, and require large device areas.

In this letter, we propose a new photodetector, the quantum dot spectrometer (QDS). The QDS consists of an inhomogeneously broadened quantum dot plane that captures the spectral channels of the optical signal and a resonant-tunneling structure that performs spectrally sensitive electronic read-out. The structure functionality resembles that of an ordinary spectrometer with the size, however, of a typical semiconductor photodetector.

For illustration purposes, we present a design on the InAs/GaAs/$Al_xGa_{1-x}As$ material system. This material system offers several advantages: First, it is the most commonly studied and most developed lattice-matched heterostructure and thus the best controlled from a technological point of view. Second, InAs/GaAs was the first system where very small (below 12 nm in diameter) self-assembled quantum dots were produced by the Stransky–Krastanow growth,[1] a technique available today in many laboratories. Third, this system provides $Al_xGa_{1-x}As$ barriers high enough to allow the design of two quantum wells with different Al composition. As discussed below, this condition is necessary for the proposed device to work.

Figure 1 shows the basic band diagram of the proposed structure. The QDS has two distinct functional units, a quantum dot plane to capture spectral features and a resonant-tunneling structure to read them out. The dots in the plane should exhibit an inhomogeneous size distribution. Such inhomogeneity is common in current quantum dot technology where range of dot size is evidenced by spectrally broad photoluminescence signals, typically of the order of 45 meV or even larger.[2] The dots should be also small, of the order of 10–20 nm (the size typically achievable by the Stransky–Krastanow growth) to prevent the second lying confined states to be to close in energy and thus play a role in the process next described.

When a spectrally rich band limited optical signal impinges the QDS, carriers are excited in the first confined electron state of the different dots according to the different spectral lines of the excitation. The process is identical to that occurring in a quantum well photodetector excited by the same light. However, while in the latter the wavelength information stored in the kinetic energy is quickly washed out by acoustic or optical scattering processes, depending on the energy range involved, in the former the energy (wavelength) is maintained over a much longer period. This is because different spectral lines excite different quantum dots. Since the dots are spatially separated, the overlap between initial and final wave functions is small and thus the scattering is strongly reduced.

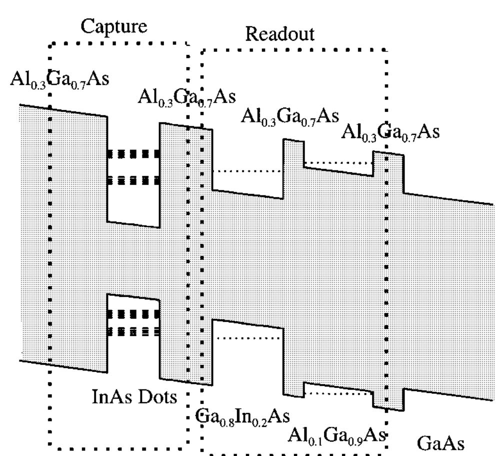

FIG. 1. Band diagram of a quantum dot spectrometer made in the InAs/GaAs/$Al_xGa_{1-x}As$ material system.

[a]Electronic mail: jimenez2@uiuc.edu

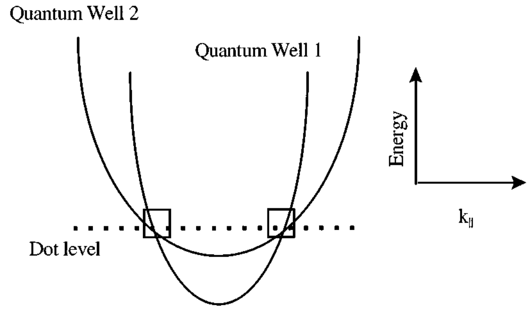

FIG. 2. Schematic representation in the energy- k space of the conservation of energy and parallel momentum between one of the dots in the quantum dot plane and the two quantum wells.

Once the spectral information has been captured in the dots, it is necessary to use a read-out mechanism capable of keeping the spectral information intact. An obvious solution to this problem would be to use a second plane of quantum dots coupled to the first plane through a tunnel barrier. This second quantum dot plane would have to fulfill the following two requirements: first, it should be uniform enough to display a strongly peaked density of states; second, it would have to be made of a wider band gap material, so that absorption in this second plane is negligible.

For every different applied voltage, only one state of the inhomogeneously broadened first quantum dot plane would align with the strongly peaked density of states of the second quantum dot plane producing a current spike. The current–voltage characteristic of the device would thus display a spectrum in which the voltage axis will correspond to the wavelength axis of conventional spectrometer, while the current axis would replace the optical intensity of the signal.

The first of the two requirements, that of having a highly homogeneous second quantum dot plane, is presently not feasible. A more realistic approach to spectrally sensitive read-out is to use a resonant-tunneling structure formed by two wells of different materials. As illustrated in Fig. 1, this could be achieved using the following layer sequence: $Al_{0.3}Ga_{0.7}As-In_{0.2}Ga_{0.8}As-Al_{0.3}Ga_{0.7}As-Al_{0.1}Ga_{0.9}As-Al_{0.3}Ga_{0.7}Ga-GaAs$. The spectrally sensitive read-out mechanism is displayed in Fig. 2 and is most easily understood with the help of the following set of equations, which ensure conservation of energy and parallel momentum along the tunneling process:

$$E_{\mathrm{dot}}=E_{\mathrm{qw1}}+\alpha V+\frac{\hbar^2 k_{\|}^2}{2m_1}, \tag{1a}$$

$$E_{\mathrm{dot}}=E_{\mathrm{qw2}}+\beta V+\frac{\hbar^2 k_{\|}^2}{2m_2}. \tag{1b}$$

E_{dot}, E_{qw1}, and E_{qw2} are the energy of a quantum dot, the first quantum well, and the second quantum well, αV and βV are the fractions of the total voltage dropped between the center of the dot and the center of the first and second quantum well, m_1 and m_2 are the effective masses of the electrons in the first and second quantum well, and $\hbar k_{\|}$, the crystal momentum parallel to the interface. From Eqs. (1a) and (1b), we obtain:

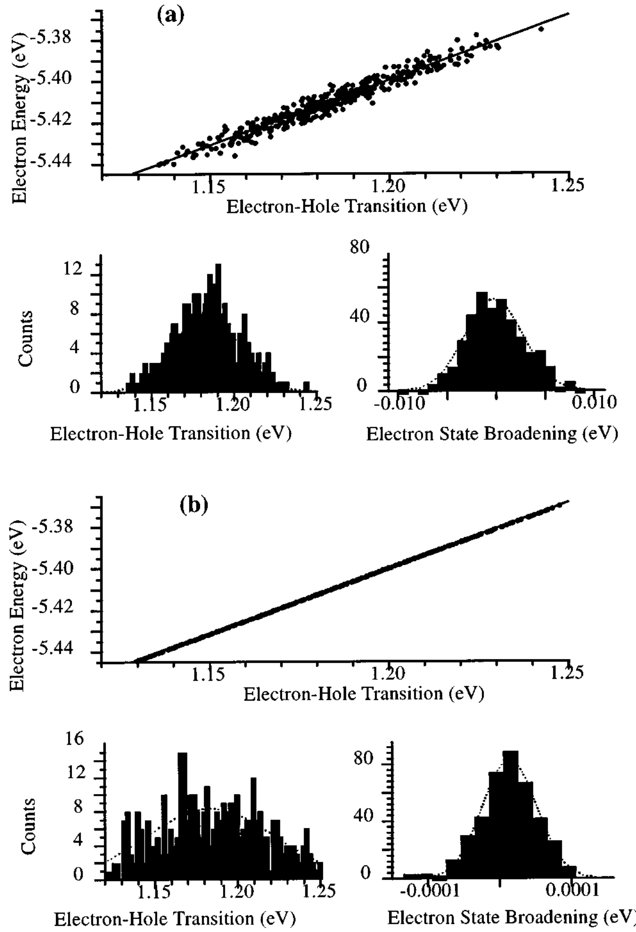

FIG. 3. Energy of the electron in the conduction band versus electron–hole energy transition for a set of pyramidal $InAs-Al_{0.3}Ga_{0.7}As$ quantum dots of variable dimensions. The size distribution of dots follows a Gaussian distribution centered at a pyramid of 12 nm base width, 6 nm pyramid height, and wetting layer of 0.6 nm. In (a), all four relevant dimensions of the dots (base size in the X direction, base size in the Y direction, pyramid height, and wetting layer) are uncorrelated. In (b), all are correlated.

$$E_{\mathrm{dot}}=\frac{E_{\mathrm{qw1}}+\alpha V-(m_2/m_1)(E_{\mathrm{qw2}}-\beta V)}{1-(m_2/m_1)}. \tag{2}$$

Equation (2) relates one to one the energy of a single quantum dot to a specific voltage. Thus setting V sets the spectral channel read by the detector. Note the importance of having two quantum wells of different materials (different masses) to make the denominator of Eq. (2) different from zero and thus Eq. (2) valid. Note also that Eq. (2) does not depend on $k_{\|}$.

The key figure of merit of the device is its optical channel capability, that is, the number of independent wavelengths it will be capable of detecting. This channel capability is limited by the fact that two quantum dots of different size in the same plane with the same optical transition (energy difference between the confined state in the conduction band and in the heavy hole band), can have different excited energies (the electron in the conduction band state). This situation occurs ultimately because the conduction band profile of the dots is only affected by the hydrostatic component of the strain, while the heavy hole profile is affected, in addition, by the biaxial component. And both components depend differently on the different dimensions of the dot.

To study this problem, we have performed two different simulations. The simulation software[3] first calculates the three-dimensional (3D) strain distribution using a nonuniform grid finite difference scheme, then it computes the bands and the effective masses up to second order in **k**, and third, it solves the 3D Schrödinger equation in the effective mass approximation using the same nonuniform grid.

The first simulation was performed over a set of pyramidal quantum dots in which each of the relevant dimensions (pyramid base lengths in the X and Y directions, pyramid height, and wetting layer thickness) was modified independently by four random numbers by at most 10% about a fixed value.[4] The second simulation was performed over a set of pyramidal quantum dots in which each of the relevant dimensions was modified by the same random number by at most 10% about the same fixed value. The results are displayed in Fig. 3. Simulation 1 [Fig. 3(a)] models the most pessimistic scenario, there where all four dimensions are uncorrelated. In this scenario, the same optical transition produces excited states differing 15 meV in energy, leading to only six possible channels (90 meV/15 meV). Simulation 2 [Fig. 3(b)] models the most optimistic scenario, there where all the dot dimensions are correlated. Experimental evidence of this size correlation has been reported in the literature.[5] In this case, the same optical transition results in excited states differing at most by 0.2 meV, leading to an enormous increase of the number of optical channels. The real case will lie between these two extreme possibilities. It is important however to note that even in the worst scenario we still have six spectral channels.

The picture described up to this point is obviously not as bright when scattering is introduced. To reduce the effects of scattering one must carefully design the width of all three barriers. The following considerations have to be addressed: First, the first barrier has to be wide enough to reduce spatially indirect absorption between the quantum dot plane and the first quantum well. Second, the barrier between the two quantum wells has to be thin enough to reduce the time spent by the electron in the first quantum well and thus the chances of the electron to be scattered.

Finally, the QDS here proposed will suffer from low responsibility. This problem is intrinsic to any photodetector using only one quantum plane (one quantum well, for example). In the case of the QDS the problem is aggravated by the fact that for each channel only a fraction of the dots in the plane are active. That is the cost one pays to include the frequency as an information carrier. More sophisticated structures including front and back Bragg reflectors, or structures with the unit described here repeated over several periods, will increase the responsibility and are currently under investigation.

In summary, we have proposed a new type of photodetector, the quantum dot spectrometer, sensitive not only to the number of excited carriers (the ''0''s or ''1''s of an optical digital signal), but also the wavelength at which they are generated, without compromising the integration capability. The device relies on the ability of an inhomogeneous plane of dots to capture the spectral information of the optical signal, and of a resonant-tunneling device to perform the spectrally sensitive read-out.

J. L. Jimenez and L. R. C. Fonseca want to thank, respectively, the Beckman Institute Fellowship and the CRI Grant of the UIUC for their support. This work was partially funded by AFOSR Grant Nos. F49620-91-1-0163 and ARO DAAH04-95-1-0190.

[1] D. Leonard, M. Krishnamurthy, C. M. Reaves, S. P. Deenbaars, and P. M. Petroff, Appl. Phys. Lett. **63**, 3203 (1993).
[2] R. Leon, S. Farfard, D. Leonard, J. L. Merz, and P. M. Petroff, Appl. Phys. Lett. **67**, 521 (1995).
[3] The software and data used are similar to those used in M. Grundmann, O. Stier, and D. Bimberg, Phys. Rev. B **52**, 11969 (1995), but with a strain-corrected electron and heavy hole mass.
[4] The center design corresponds to a pyramid of 12 nm base and 6 nm height, lying over a wetting layer 0.6 nm height. The random numbers used follow Gaussian distributions.
[5] R. Notzel, J. Temmyo, A. Kozen, T. Tamamura, T. Fukui, and H. Hasegawa, *Proceedings of the 7th Conference of Modulated Semiconductor Structures*, Madrid, Spain, 1995.