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Carrier emission from the electronic states of self-assembled indium arsenide quantum dots

S.W. Lin [a], A.M. Song [a], M. Missous [a], I.D Hawkins [a], B. Hamilton [a], O. Engström [a,b], A.R. Peaker [a,*]

[a] *Centre for Electronic Materials, Devices and Nanostructures, School of Electrical and Electronic Engineering, University of Manchester, Manchester M60 1QD, UK*
[b] *Chalmers University of Technology, Department of Microtechnology and Nanoscience, SE-412 96 Göteborg, Sweden*

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Abstract

We have used the new technique of high resolution (Laplace) transient spectroscopy to examine the electronic states of ensembles of self-assembled quantum dots of InAs in a GaAs matrix. These have been produced by solid source MBE. We have monitored the s and p state occupancies as a function of time under thermal excitation over a range of temperatures after electrons have been captured by the quantum dots with different Fermi level positions. This can provide more information about the interaction of the dots with the host matrix than is possible with optical techniques and gives new fundamental insights into how such dots may operate in electronic devices such as memory and sensors. The increase in resolution of Laplace transient spectroscopy over conventional experiments reveals quite specific rates of carrier loss which we attribute to tunnelling at low temperatures and a combination of thermal emission and tunnelling as the temperature is increased.

Keywords: Quantum dot; Indium arsenide; DLTS; Tunnellings; Trapping; Electron emission

1. Introduction

Over the last 20 years, there has been a formidable amount of work applied to understanding quantisation effects in wells and dots in a range of semiconductor systems. The vast majority of this work has centred on optical studies (luminescence and absorption) and on transport. There has also been a very strong theoretical input, which has enabled the community to develop a comprehensive understanding of these systems. In recent years, developments in growth techniques have meant that planar arrays of self-assembled quantum dots can be produced with relative ease in lattice mismatched systems by exploiting the Stranski–Krastanow mechanism of strain relaxation [1]. This has led to an explosion of scientific and technological interest which initially has focused on optical properties. Quantum dots exhibit atomic-like features compared to the broadband structures of bulk semiconductors, and so are rather interesting from the point of view of photo detectors and LASERs. In the latter application, the extremely high radiative efficiency of self-assembled quantum dots and the narrow luminescence line structure are very attractive from a technological viewpoint.

However, relatively recently, attention has been drawn to the potential that quantum dots have in data processing and data storage devices, applications which do not necessarily involve optical interactions. In these applications, the key parameters are the mechanism of charge capture by the dot, charge retention and its emission under external stimuli. Some of these parameters can be inferred from optical measurements but a much more appropriate methodology would be to measure these parameters directly and to gain a fundamental understanding of the mechanisms involved. Such an understanding is probably the only route to properly engineered quantum dot memory devices.

Although there has been a spasmodic effort over a long period of time to study the electrical properties of quantum wells (e.g. [2,3]) and quantum dots (e.g. [4–6]), the interpretation of the data is problematic. Perhaps the most fruitful work in the last few years has been effected by growing a plane of self-assembled quantum dots in a semiconductor doped to a level whereby a depletion region formed underneath a Schottky

* Corresponding author.
E-mail address: peaker@manchester.ac.uk (A.R. Peaker).

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barrier could be modulated so that its edge passed through the plane of quantum dots, according to the applied bias. The presence of charge exchange with the dots is observed in capacitance voltage measurements, admittance spectroscopy and perhaps, most fruitfully, deep-level transient-spectroscopy. In this latter technique, the depletion region is made narrow by the application of a zero or low applied reverse bias, under which circumstances the dots have the opportunity to capture carriers and then in the second phase of the experiment the depletion region is extended by the application of a larger reverse bias, so the dots are contained in the depleted region. In the attempt to return to equilibrium charge is released from the dots driven by thermal energy. By conducting the experiment at a range of temperatures and observing the emission rate an Arrhenius plot can be constructed, the slope of which represents an energy.

The interpretation of what this energy means is a far from trivial task. A number of publications have appeared recently, which address this problem. By careful adjustment of the filling level, Engström et al. [5] effected selective filling of the s-like quantised states. Schultz et al. [6] extended this work and included in their interpretation tunnelling from the confined states. In this volume, the statistics of the tunnelling process is considered in much more detail by Engström et al. [7].

The technique of DLTS provides a fundamentally different approach to the study of confined states compared to photoluminescence. DLTS opens up the possibility of studying wells in a one-carrier system, so that at least in principle dipole effects are under control. However, the emission process from which the DLTS spectra derive is rather complex. Fig. 1(i) provides a schematic illustration of the conduction band in the vicinity of the quantum dot. At this stage in the discussion, it should be pointed out that the detail of the system is dramatically affected by the materials and size of the dots and so as a starting point we will consider indium arsenide dots in a gallium arsenide matrix, with dots approximately 10 nm high and 20 nm wide. Such a system is likely to possess 6 quantised states—2 with s-like character and 4 with p-like character. When the dot captures a carrier (in this case, an electron) the bands bend, effecting a Coulomb blockade which makes capture of a second carrier more difficult (Fig. 1(ii)). In the experimental case that we are considering, capture takes place in a neutral region of the semiconductor as represented by (ii) in the diagram, whereas emission takes place in a high field region (within the depletion region) as illustrated in (iii).

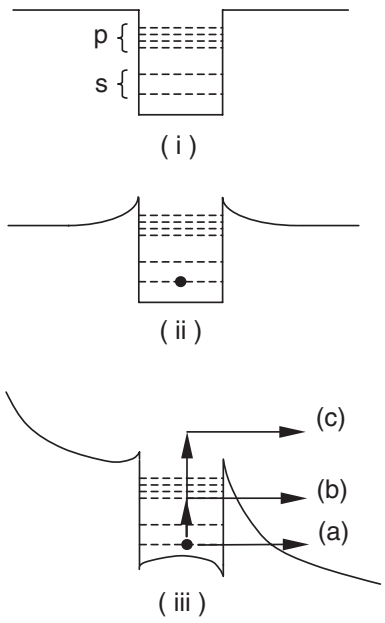

Fig. 1. Illustration of the conduction band in the vicinity of a quantum dot. (i) illustrates the uncharged dot in the neutral region of the semiconductor. The dotted lines indicate the quantised states with s and p character. (ii) shows band bending in the neutral region associated with the capture of one electron at the dot. (iii) illustrates the charged dot in the depletion field (the condition for observing carrier emission) and shows possible mechanisms of carrier loss from the s and p states.

It is evident that there are a number of mechanisms for release that can take place. The most obvious and the one which dominates the thinking of early papers is a simple thermal excitation from the s states to the band. Conceptually, this will result in two peaks in the DLTS spectrum with emission rates which relate to the two s states. However, another alternative is that the electrons are excited to the p states, from which they are then thermally emitted to the conduction band or, as has been mentioned previously, electrons are excited thermally from the s states to the p states and from there they tunnel through the barrier into the band, this is shown as process (b). Process (a) must also be considered and that is the possibility of tunnelling from the s states directly into the band. In all cases, the electrical techniques can only detect charge exchange between the confined states and the band (bound to free transitions) so that rearrangement of charge among the quantised states does not result in any detectable signal using these techniques.

All the above processes could occur but the relative probabilities will depend on temperature, the electric field (which is a function of applied voltage and the carrier concentration of the matrix) and on the matrix and quantum dot materials.

In principle, it is possible to separate the processes using carefully designed thermal emission experiments. However, there are two major obstacles in the experimental realisation of such measurements. The first is that all such measurements to date have been undertaken on ensembles of quantum dots. Unfortunately, the Stranski–Krastanow self-assemble technique, which relies on the relief of strain in lattice mismatched systems, produces a distribution of dot sizes and hence within the ensemble there is a distribution of energies of the quantised states. In luminescence, it is technically possible to examine a single dot and a number of publications have resulted from such work (e.g. [8,9]). Similarly, the absorption spectra of a single dot has also been determined by using refined optics [10] or photoconductivity [11], at the present time the measurement of individual dots has not been achieved using DLTS methods. The second issue is specific to DLTS. Because the technique is a thermally driven process, the energy resolution will be limited to a value of the order of kT, where T is the measurement temperature. However, this is unlikely to