Charge Storage in Self-Assembled CdTe Quantum Dots

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Abstract. We demonstrate storage of photoexcited electrons in a layer of self assembled CdTe quantum dots embedded in a field-effect structure. We study the storage efficiency with respect to the duration of the photoexcitation pulse. The electrons persist in the quantum dots for as long as 9 milliseconds.

Self assembled quantum dots (QDs) are promising candidates for many spin-based applications [1]. In particular, spin memory devices are expected to provide a significant advance with respect to modern day instruments. Their operation requires injecting spin polarized electrons into QDs, preventing them from escaping, and eventually reading them out. These processes have already been reported in a series of papers. Finley et al. showed an electron read-out via monitoring conductivity of a 2D electron channel [2]. Lundstrom et al. demonstrated storage of electrons and holes in two separate layers of dots [3]. More recently, Young et al. and Heiss et al. reported on optical charge generation, storage, and readout from a single QD [4, 5]. The papers quoted above all concern InAs or InGaAs QDs.

We investigate charge storage in self assembled CdTe QDs in ZnMgTe barrier. This II-VI system is interesting from the point of view of possibility of doping the structure with magnetic ions. Manganese doped QDs are already investigated by several groups [6]. Doping of the charge reservoir on the other hand allows an electrical injection of spin polarized carriers providing a testbed for investigations of many body spin interactions in QDs.

In this report, we demonstrate the operation of our charge storage device. The electrons are optically generated and stored in an ensemble of dots embedded in a \textit{p-i-}Schottky structure. Application of a bias pulse results in an injection of holes, which upon recombination with the stored electrons provide an optical readout. The charge remains stored at a timescale of milliseconds.

The sample was grown by molecular beam epitaxy on a (001)-oriented semi-insulating GaAs substrate. First, a thick 4 \textmu m ZnTe buffer layer was deposited, \textit{p}-doped with nitrogen using an RF plasma source. The doping level was of the order of $10^{18}$ acceptors per cm$^2$. The buffer acted as the back contact and a hole reservoir. After a 15 nm of an undoped Zn$_{0.9}$Mg$_{0.1}$Te spacer, a layer of CdTe QDs was grown using a method developed by Tinjod \textit{et al.} in which a strained layer of CdTe is covered with amorphous tellurium in order to change the surface energy [7]. After tellurium evaporation, the QDs are formed, a process which we monitored by recording the changes of the reflection high energy electron diffraction (RHEED) pattern.
dots are approximately lens shaped with the diameter in the range between 10 and 40 nm, and heights in the range between 2 and 8 nm. The dot layer is covered with a 100 nm wide Zn$_{0.9}$Mg$_{0.1}$Te barrier and another Zn$_{0.7}$Mg$_{0.3}$Te blocking barrier, preventing the escape of carriers to the surface. On top, a semitransparent Ti/Au Schottky gates are deposited. The gates are defined by photolithography. They are rectangular – 10 × 100 μm in size and separated by about 100 μm. As a function of temperature, the structure reveals usual diode I-V characteristics down to about 5 K, when the carriers are frozen out at the acceptor sites.

The charge storage experiment relies on a measurement of the ensemble QD photoluminescence (PL). The emission is excited either above or below the Zn$_{0.9}$Mg$_{0.1}$Te barrier with a 472 nm or 532 nm diode pumped semiconductor laser beam, respectively. The beam is modulated by an acousto-optic modulator, providing pulses with duration from 10 ns to infinity. The spot diameter is approximately 100 μm, so the beam illuminates only one diode, but also an unprocessed region around it, yielding a background, bias independent signal. The PL signal is measured by time correlated single photon counting setup consisting of an avalanche photodiode coupled to a monochromator and a multichannel analyzer. Overall temporal resolution of the system is better than 200 ps. The measurements are performed at a temperature of 15 K, ensuring efficient diode operation.

The operation principles of our memory device is shown in Fig. 1. The writing phase of the experiment consists in exciting the sample below barrier under reverse bias. Under such conditions, electrons and holes are generated in the dots not in the barrier. The triangular barrier between the dots and the reservoir is decreased resulting in the holes tunneling out to the reservoir. After the laser is switched off, the electrons remain stored in the QD layer as long as the bias remains reverse. After a controlled time delay, a forward bias pulse is applied, resulting in an injection of holes from the reservoir to the dots upon which the holes and electrons recombine providing a readout of the stored charge.

In the experiment, we simultaneously vary the period of the laser and bias pulses in the range between 100 ns and 10 ms. We control the magnitudes of write and read voltages and vary the time delay between the end of the laser pulse and the start of the readout. In the following, we show results of measurements where the write/read bias are equal to zero and +6 V, respectively. Writing therefore occurs due to a built in voltage, which amounts to -0.5 V.

In Fig. 2a), time traces of the PL signal are shown. The top trace is collected under constant excitation below the barrier, with bias modulation. The PL intensity under reverse bias results from an interplay of the recombination and hole tunneling times, and from a background PL from outside the diode. The signal abruptly increases, when a forward bias pulse is applied at a delay of ~2300 ns. It is a result of an enhancement in carrier capture. The shape of the forward bias feature in the time traces points out to two types of carrier capture. The fast, initial signal increase marks the hole injection to the dots from the reservoir. This is evidenced in the bottom
trace, where both the bias and the laser are modulated. Photoexcitation inscribes the charge in the dots during the write phase. The laser is then switched off and the charge is stored until the forward read pulse is applied. This is accompanied by an appearance of a distinct PL flash, lasting for several tens of nanoseconds. This PL emission is due to a recombination of the stored electrons with electrically injected holes. This peak coincides temporally with the sharp feature in the constant excitation trace (top). We assume that the slow feature in these traces reflects the capture of photocreated electron and hole pairs by the QD potential. The pairs eventually recombine in the dots, instead of being separated by the electric field as it occurs in the write phase. The middle trace in Fig. 2a) shows a PL trace under pulsed excitation and zero bias. It proves that the PL flash is solely due to the electrically injected holes.

Exciting the PL signal above the Zn$_{0.9}$Mg$_{0.1}$Te barrier band gap does not lead to any charge storage. Indeed, under such conditions, photoexcited electron-hole pairs are dissociated in the intrinsic region and the electrons, instead of being captured by the QDs are trapped at the barrier/blocking barrier interface producing a space-charge effect. As shown by Smith et al, a charge can be efficiently stored at this interface where an electric field induced triangular potential well develops [8]. However, we do not observe any readout PL, which can be due to the fact that the distance between this triangular well and the QDs is in our case 100 nm compared
to 15 nm in the report quoted above.

The amount of charge stored in the QD layer depends obviously on the write time. In Fig. 2b), we show PL time traces for various durations of laser excitation. An increase of the readout peak intensity is clearly seen. Its integrated intensity as a function of the laser pulse duration is shown in the inset. After an initial increase, the readout peak intensity saturates for laser pulse duration of about 10% of the bias modulation period. We assume that at this pulse duration we effectively store approximately the same amount of electrons in each of the photoexcited dots.

The charge readout peak can be traced with increasing the time delay between the laser switch-off and the application of the readout pulse. In Fig. 2c), we present a PL time trace for the longest of the investigated delays, equal to 8.9 ms. The readout peak can be clearly resolved. We find a fivefold decrease of the readout peak intensity with increasing this delay from 1 µs to 8.9 ms. This decrease reflects the loss of the stored charge. The decrease is approximately logarithmic suggesting that electron leakage rate is changing with the delay - a phenomenon which we attribute to a modification of electron escape rate with decreasing the amount of charge stored in the dot layer. We also observe a significant increase of the electron leakage with increasing write bias, suggesting a tunneling escape mechanism [9]. Our charge storage time of the order of tens of milliseconds is much shorter than observed in InAs QDs, where optical and electrical readout evidenced storage times in the range of seconds [3] and hours [2], respectively. However, we expect that by addressing individual QDs by quasiresonant excitation, this charge storage time can be substantially extended.

In summary, we demonstrated how electron charge can be efficiently created, stored and read out from a layer of self-assembled CdTe quantum dots. We showed that the storage efficiency saturates with increasing excitation (write) time. Electrons persist in the quantum dots for a time of ~ 10 ms.

This work was partially supported by Polish Ministry of Science and Education grant no. 0634/BH03/2007/33.

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