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Optical properties of hybrid quantum dot/quantum well active region based on GaAs system

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We experimentally investigate the optical properties of a novel hybrid material/structure consisting of a GaInNAs quantum well and stacked InAs/InGaAs quantum dot layers on GaAs substrate. We demonstrate that the strong quantum confined Stark effect within the quantum well can effectively control well-dot detuning when reverse bias voltage is applied. With a combination of low- and room-temperature time resolved luminescence spectra we infer device absorption recovery time under 30 ps. These properties could be utilized in high-speed optoelectronics devices, in particular electro-absorption modulated lasers and reconfigurable multisection devices, where the hybrid quantum dots–quantum well material system could offer easily and rapidly interchangeable function, i.e., emission gain or variable attenuation, of each section depending on the external bias.

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the hybrid p-i-n sample, both a single Ga0.63In0.37N0.015
As0.985/GaAs 6 nm QW and six stacked InAs/In0.15Ga0.85As/
GaAs DWELL intrinsic samples have been grown separately
as well.

Room temperature (RT) photoluminescence (PL) meas-
urements (confocal geometry, Ti:Sapphire 800 nm excitation
laser) of the QD sample [Fig. 2(a)] showed a ground state
(GS) emission at 1310 nm and a first excited state (1ES)
emission peak at 1210 nm while for the QW sample the emis-
sion peak was centred at 1260 nm. RT PL spectra of the p-i-n
sample were dominated by QD features with no clear contri-
bution peak is centred at 1260 nm. RT PL spectra of the p-i-n
emission peak at 1210 nm while for the QW sample the emis-

FIG. 1. The band structure of the proposed hybrid structure material consist-
ing of six InAs DWELL layers and GINA QW on n++ GaAs substrate to-
gether with cross-sectional transmission electron microscopy image of the
active region and with detailed active region composition of the hybrid p-i-n
sample.

FIG. 2. PL spectra of separate InAs QD and GINA QW intrinsic samples at
(a) room temperature and (b) at 14 K. The temperature dependent PL peak
energy emission proving minimal carrier localization effect in the intrinsic
QW sample is shown in inset. (c) Low (14 K) temperature reverse bias vol-
tage (0 V-6 V) dependent PL of hybrid QD-QW showing the QCSE within
the QW. The inset shows the fitted QW peak wavelength as a function of
bias and its redshift of 15 nm, while the QDs indicate no shift in wavelength.

The spectral evolution of the hybrid structure as a func-
tion of the reverse bias voltage (RBV) measured at 14 K is shown in [Fig. 2(c)]. The maximum RBV of –6 V, together
with built-in voltage of 0.8 V, corresponds to total field
strength of 110 kV/cm. For RBV ranging from –6 V to 0 V, the integrated PL intensity had a linear relationship with
applied bias. From a multi-peak fitting procedure (where all
the QD states were fitted by Gaussian curves, whilst the QW
states were fitted by a single asymmetrical function) the QW
peak was fitted by the Varshni model with 

\[
E = E_0 - \frac{a}{T^2} + \frac{b}{T} - \frac{c}{T^3}
\]

where \(E_0\) is the high-temperature PL peak energy,
\(a\) is the constant related to the band gap narrowing,
\(b\) is the constant related to the carrier localization
energy in the QW and in our case the indium concentra-
tion is around 35%. Third, and lastly, the GINA QW inside the hybrid p-i-n sample
underwent in-situ annealing during the top p-doped cladding layer growth at 600 °C. This leads to the atomic
reorganization and a much more even nitrogen distribution
thereby minimizing nitrogen clustering and leading to a crys-
tal quality improvement. All these effects suggest that one
should neglect the carrier localization phenomena inside
the QW of the hybrid p-i-n sample.

For operation in optical modulator and saturable
absorber devices, the absorption recovery time is a crucial
parameter. To study the carrier dynamics, we performed a
set of time-resolved photoluminescence (TRPL) experiments
for the hybrid p-i-n and GINA QW sample (for thermal prop-
erties measurement). With its higher saturation fluence and
expected faster recovery times, we mainly focused on the dynamics of the GINA QW, but the QD signal was analyzed as well. To pump the structure, a 300 fs pulsewidth, mode-locked Ti:Sapphire laser tuned to 1015 nm was used. At this excitation wavelength and with a low (14 K) sample temperature, the photo-generation of electron-hole pairs is avoided both in the GaAs barriers and in the InGaAs wetting layers (WLs), thus preventing the creation of a carrier reservoir. The highest energy state excited is the second excited state inside the QD. Specific care was also taken to minimize the generation of higher energy carriers through the two-photon absorption process. The GINA QW ground state electron-hole (e1-hh1) PL lifetime depends on four relaxation/escape mechanisms: radiative recombination, $\tau_{rad}$; non-radiative recombination through NRR centers, $\tau_{nonrad}$; thermionic emission, $\tau_{th}$; and field induced tunnelling, $\tau_{tun}$. As was mentioned earlier, the 125 nm GaAs spacer prevents any carrier relaxation/tunnelling into the QD ground state from the QW and from the QD excited states into the QW. Thus, the only other mechanism acting to decrease the QW PL decay rate would be the electron-hole pair generation by absorption of photons originating from radiative recombination in the higher QD states (i.e., 2ES and 1ES) inside the IAR. However, this only makes a minor contribution and so can be neglected. Therefore, the GINA QW can be considered to be an isolated system and the total QW PL decay rate can be expressed as

$$\tau^{-1} = \tau_{rad}^{-1} + \tau_{nonrad}^{-1} + \tau_{th}^{-1} + \tau_{tun}^{-1}. \quad (1)$$

In order to better understand the dynamics within the QW region and the significance of the individual contributions, two specific measurements were carried out. The first experiment was TRPL as a function of RBV performed at 14 K, where both thermionic emission and NRR processes are significantly suppressed, and thus the dominant contribution is from field induced tunnelling. External biases, varying from 0.0 V down to $-8.0 \text{ V}$, were applied. In the streak images [Fig. 3(a)], we can observe not only the QW redshift as expected from the PL measurement, but also dynamical features indicative of radiative recombination. To quantify the decay times of the QW in the hybrid structure, we have sectioned the streak images along its peak wavelength (denoted by dashed lines) and obtain the decay traces [Fig. 3(b)]. After deconvolving the measured data with the system response [Fig. 3(b) dashed line], we proceeded with fitting. The QD GS decay times were extracted at its peak wavelength (1200 nm) and the voltage insensitive value of around 1400 ps was found and is in the typical range of InAs DWELL systems measured at low temperature. As the QD GS emission, with its 60 meV width [Fig. 2(b) QD GS fitting], overlaps the emission from the QW (especially at higher RBV), we have fitted the decay traces with a double exponential function with a fast component (voltage sensitive) belonging to the QW emission and a slow component (voltage insensitive) to the QD GS blue tail. With increasing RBV, the photo-generated carriers effectively tunnel through the GaAs barrier into the external circuitry and decay times shorten. The extracted QW decay times $\tau_{QW}$ [Fig. 3(b) inset] exponentially follow the applied RBV with the QW decay time varying from 150 ps (0.0 V) down to 74 ps ($-8.0 \text{ V}$). The slow component decay times $\tau_{QD}$ were around 1400 ps, which is in agreement with the QD GS decay times extracted at 1200 nm discussed above.

In the second experiment, the NRR and thermal escape contributions on the QW PL decay time have been determined. We measured the intrinsic QW structure (no external voltage applied) PL decay under different temperatures ranging from 13 K up to 290 K under the same excitation conditions as above [Fig. 4]. The impact of temperature increase was twofold. First, the thermal activation of the NRRs induces a progressive change of the QW PL decay curve shape from a convex line (13 K) to a straight line (160 K) in semilog scale. $^{21}$ As the temperature increases further and reaches

![Fig. 3. The TRPL streak images at 0.0 V, $-4.0 \text{ V}$, and $-8.0 \text{ V}$ showing both wavelength positions and temporal dynamics of the QD and QW states.](image-url)
190 K, the carrier thermal energy $k_B T$ is approximately equal to half of the hh-barrier offset thus leading to thermionic emission. This hole leakage leads to further shortening in PL decay times down to 50 ps at 290 K. Thus at room temperature, together with using external bias to induce tunneling, we can easily expect PL lifetimes shorter than 30 ps, which become suitable for high speed direct modulation.

In summary, we have shown the properties of a GINA QW embedded in a hybrid p-i-n structure together with six stacked InAs/InGaAs QDs layers. As QDs show low sensitivity to the applied voltage in terms of QCSE shift and carrier density, and also QWs stacking (double QW) could enhance device performances.

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FIG. 4. Temperature dependent (13-290 K) TRPL measurement of GINA QW showing first the thermal activation of NRR centers responsible for radiative recombination decay time shortening and further shortening due to the hole leakage (thermionic emission) at elevated (>190 K) temperature.