FAST, MULTI-BAND PHOTON DETECTORS BASED ON QUANTUM WELL DEVICES FOR BEAM-MONITORING IN NEW GENERATION LIGHT SOURCES

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Abstract

In order to monitor the photon-beam position for both diagnostics and calibration purposes, we have investigated the possibility to use InGaAs/InAlAs Quantum Well (QW) devices as position-sensitive photon detectors for Free-Electron Laser (FEL) or Synchrotron Radiation (SR).

Owing to their direct, low-energy band gap and high electron mobility, such QW devices may be used also at Room Temperature (RT) as fast multi-band sensors for photons ranging from visible light to hard X-rays. Moreover, internal charge-amplification mechanism can be applied for very low signal levels, while the high carrier mobility allows the design of very fast photon detectors with sub-nanosecond response times.

Segmented QW sensors have been preliminary tested with 100-fs-wide 400 nm laser pulses and X-ray SR. The reported results indicate that these devices respond with 100 ps rise-times to such ultra-fast laser pulses. Besides, linear scan on the back-pixelated device has shown that these detectors are sensitive to the position of each ultra-short beam bunch.

INTRODUCTION

Several Free-Electron Lasers (FEL) and Synchrotron Radiation (SR) applications require radiation-hard and fast *in-situ* detectors for diagnostics and calibration purposes [1].

The opportunity to use QW devices for photon detection has been proposed in infrared region [2]. Recently, we have reported on QW detectors working in the ultraviolet (UV) and X-ray regions for FEL and SR sources [3, 4]. These QW devices give the possibility to detect a broad energy range of incoming photons, due to the low and direct band gap of the active layers. Furthermore, high carrier mobility at room temperature (RT) makes it possible to detect ultra-fast light pulses operating in either air or vacuum without cooling equipment. Therefore, epitaxially grown metamorphic InGaAs/InAlAs QW devices are here proposed as fast, solid-state detectors for beam monitoring applications.

These novel detectors are good candidates to sense the position and the intensity of a beam meeting the demanding time-resolution requirements posed by recent SR and FEL sources. To this aim, the performances of these detectors have been assessed by measuring their response to ultra-fast laser pulses.

Preliminary experiments have been carried out through a table-top Ti-sapphire laser delivering 100-fs-wide pulses with a 400 nm wavelength. The structure of the aforementioned QW devices and the main results of these the tests are reported.

QUANTUM-WELL DEVICES

Device Structure and Characterization

These devices have been grown by Molecular Beam Epitaxy (MBE) at the CNR-IOM TASC Laboratory, Trieste. The starting material is a 500 µm thick epi-ready semi-insulating GaAs substrate. As shown in Fig. 1, in order to smooth the substrate surface a 200 nm thick GaAs layer was grown on its top, followed by a 200 nm thick GaAs/AlGaAs superlattice, which blocks the impurities from the bulk. Another 200 nm thick GaAs layer was introduced before an $In_xAl_{1-x}As$ step-graded buffer layer (BL) with increasing x from 0.15 to 0.75; this allows the lattice constant to be tuned in order to reduce the residual strain due to the lattice mismatch [5]. A 25 nm thick $In_{0.75}Ga_{0.25}As$ QW containing a 2D Electron Gas (2DEG) was placed in between 50 nm thick $In_{0.75}Al_{0.25}As$ barrier layers and a delta Si-doping was introduced in the upper barrier.

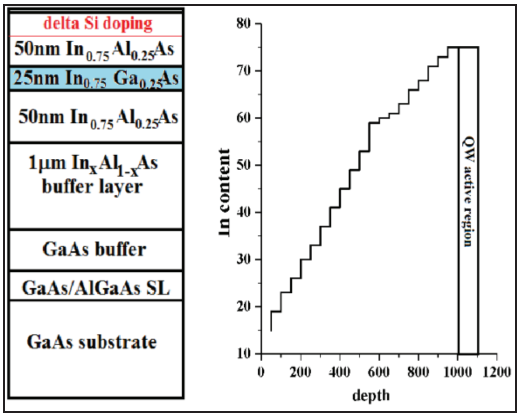

Figure 1: Layered structure of the samples and nominal profile of the In content in the step-graded buffer layer.

Hall-bar measurements were performed to characterize the charge density and the carrier mobility in the QW at room temperature, resulting in $n=7.7\times10^{11}$ cm^{-2} and $\mu=1.1\times10^{4}$ $cm^2V^{-1}s^{-1}$, respectively. Top-to-bottom resistance was found to be of the order of 100 MΩ at ambient condition, mostly determined by the substrate resistivity.

Test-Dice Fabrication

Two types of samples (with a die area of 5x5 mm^2) were prepared from 500 µm thick InGaAs/InAlAs QW wafers and the structures on the surface were fabricated by using optical photolithography (Fig. 2). In the first sample, the QW region was segmented in three different pads, leaving a QW under each pad, while the rest of the surface was chemically etched by 1.5 µm to reach the substrate. Ge/Ni/Au (30/60/130 nm, respectively) ohmic contacts were provided as readout electrodes for currents from the pads. A single 400 nm Al electrode was deposited in the back side of the die for biasing.

In the second sample, the back side of the device was pixelated with 100 µm wide clearances. Same readout electrodes were realized on each quadrant. The unsegmented QW side was covered by a single bias electrode identical to the one described above.

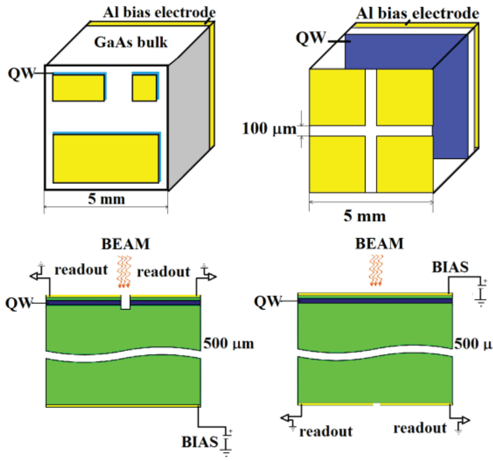

Figure 2: Schematic view of the fabricated devices.

EXPERIMENTAL DETAILS

Ultra-fast near UV pulsed laser sources are an efficient tool to characterize the presented QW detectors in terms of time response and position sensitivity. The reported experiments were carried out at the IUVS Support Laboratory of Elettra through a 400 nm titanium-sapphire laser emitting 100 fs wide pulses at a 1 kHz repetition rate. The laser beam was focused in order to obtain a 100 µm spot on the surface of the QW sensor. The power of the impinging photon pulse was varied during the tests to check the dependence of photo-generated charges.

In order to perform mesh scans, the QW devices were mounted on a XY movable stage housed in a compact vacuum chamber. This stage is driven by stepper motors which are remotely controlled by a Labview-based software. The signals from the readout pads were acquired through a 40 GS/s oscilloscope.

RESULTS AND DISCUSSION

The first measurement was aimed at assessing the pulse response of the sensor. Therefore, the laser beam was focused on the surface of the first sample in proximity of the pads. The acquired signals (Fig. 3) show sub-ns response times with 100 ps rise/fall times to laser pulses.

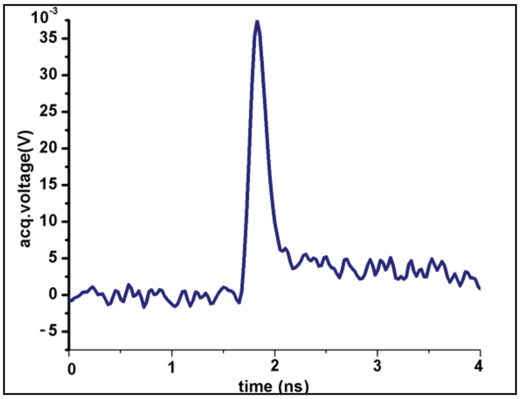

Figure 3: Response of device with segmented QW structure on the surface to the laser pulses.

Taking into account the small penetration depth of 400 nm photons, with a bias voltage as low as –10V and electron mobility as high as 10^4 cm^{2}V^{-1}s^{-1}, the charge collection time at readout pads should be of the order picoseconds, which is in agreement with the experimental results.

The area of the response pulse was estimated in terms of average incident power of the laser pulse and fitted by an allometric curve (Fig. 4), which could express the behaviour of the devices when dealing with low energy photons.

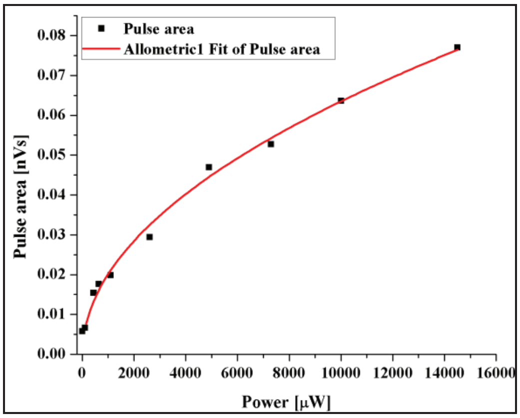

Figure 4: Peak area (time-integrated voltage pulse) dependence on incident power.

Figure 5 shows that the area of the acquired pulses is linearly proportional to the bias voltage applied from the back side of the device.

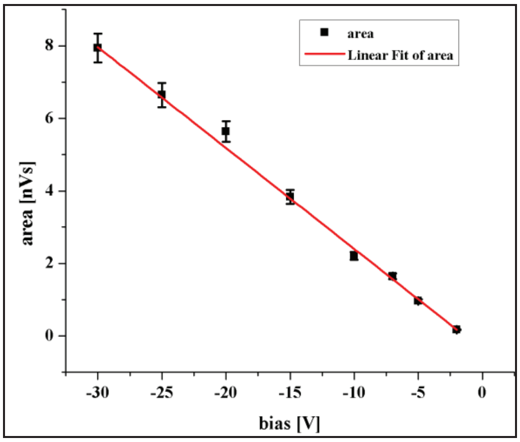

Figure 5: Area of response pulse VS bias voltage.

With the second device the position monitoring of each ultra-short laser pulse was tested by linear scans across the 100 µm clearance between the quadrants. As shown in Fig. 6a, when the beam hits one quadrant only, no current contribution from other channels is present.

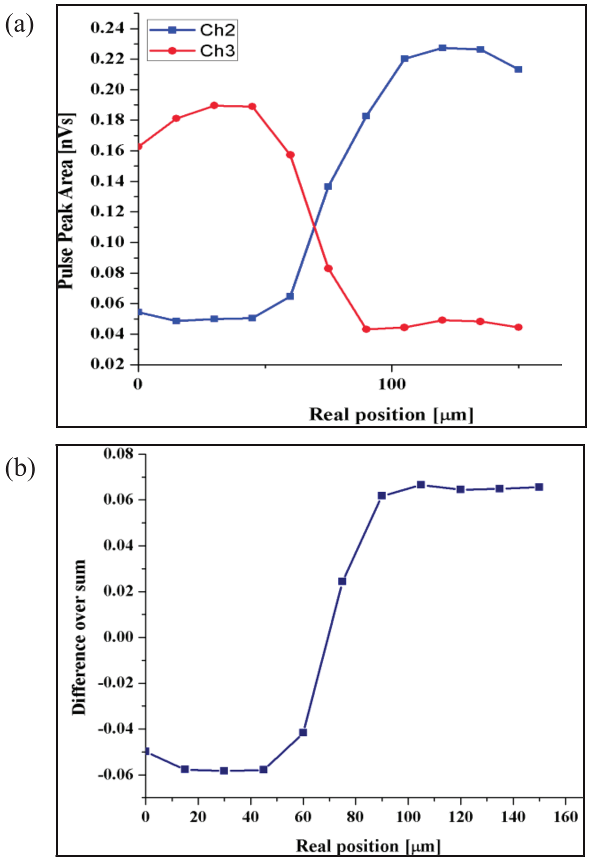

Figure 6: (a) Current switch from two channels during linear scan and (b) difference over sum.

It is evident how the two currents from each channel switch while the beam crosses the clearance. Furthermore, the difference-over-sum estimation [6] of the beam position results in a sigmoidal curve with a central linear range of about 30 µm (Fig. 6b). This proves the capability of the detector for beam position monitoring. However, the number of steps in the transition region was not sufficient for a detailed estimation of the precision of the beam-position encoding.

CONCLUSION

The capabilities of the proposed QW devices were tested in terms of beam-position monitoring and fastness of signal detection in response to the short-pulsed laser light.

Thanks to their high carrier mobility and charge-amplification from 2DEG, these detectors responded with 100 ps rise times to ultra-short near UV pulses. Furthermore, beam-position sensing behaviour was confirmed by linear scan across the 100 µm clearance isolating two quadrants.

Alternative pixels strategies are under development to characterize other performances such as charge sharing behaviour of the pixels, energy resolution, charge collection efficiency of photo-generated current, etc.

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