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Photoelectric Properties of InAs/GaAs Quantum Dot Photoconductive Antenna Wafers

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***Abstract*—In this paper, the study of the photoconductivity in self-assembled InAs/GaAs quantum dot photoconductive antenna in the wavelength region between 1140 nm and 1250 nm at temperatures ranging from 13 K to 400 K is reported. These antennas are aimed to work in conjunction with quantum dot semiconductor lasers to effectively generate pulsed and CW terahertz radiation. For the efficient operation, laser wavelengths providing the highest photocurrent should be determined. To study the interband photoconductivity of quantum dot photoconductive antennas, at room and cryogenic temperatures, we employed a broadly-tunable InAs/GaAs quantum dot based laser providing a coherent pump with power exceeding 20 mW over a 100 nm tunability range. The quantum dot antenna structure revealed sharp temperature-dependent photoconductivity peaks in the vicinity of wavelengths, corresponding to the ground and excited states of InAs/GaAs quantum dots. The ground state photoconductivity peak vanishes with a temperature drop, whereas the excited state peak persists. We associate this effect with different mechanisms of photoexcited carriers extraction from quantum dots.**

***Index Terms*—Quantum dots, semiconductors, photoconductivity**

I. Introduction

THE generation of broadband terahertz (THz) radiation, which is strongly desired for spectroscopic, imaging and security applications, particularly in a form of compact and easily transportable devices, is a major task for research and industry nowadays [1]. In this respect, photoconductive antennas (PCAs) are the most promising sources [2]. These antennas are compact, do not require high-power laser pumps and can operate in both ultrabroadband pulse and tunable continuous wave (CW) regimes of THz generation at room temperatures. Previously, when only low temperature grown gallium arsenide (LT-GaAs) was used as a PCA semiconductor substrate, bulky, mechanically-unstable and expensive Ti:Sapphire lasers were required to provide a pump at ∼800 nm wavelength, thus making the whole THz generating system large, unsteady and expensive [3]. Thus alternatives such as design of materials with a smaller bandgap in conjunction with a fiber laser pump [4], or the use of InAs/GaAs quantum dot based PCA wafers with compact semiconductor lasers fabricated from identical QD based superlattices [5], [6], have been proposed.

Materials containing InAs quantum dots (QDs) inside the GaAs lattice are one of the most versatile media in semiconductor photonic devices [7]. They have been employed as the gain medium in diode lasers [8], [9] and amplifiers [10], [11], and to form integrated saturable absorbers in short pulse in-plane diode laser emitters [12] and semiconductor saturable absorber mirrors (SESAMs) [13], [14]. InAs/GaAs QD based lasers have demonstrated sub-ps pulses at reasonably high powers [15], [16]. The exploitation of the photocurrent generation in QD based wafers resulted in their use in infrared (IR) photodetectors [17] and photovoltaic devices [18], [19].

Recently, QD based PCAs have been demonstrated to successfully generate coherent THz radiation in the pulsed [6], [20] and CW [5], [6], [21] regimes. THz generation was achieved both within a Ti:Sapphire (GaAs bandgap) and a compact QD-based laser diode (QD bandgap) pumps. To stimulate further progress in the quantum dot based PCA THz systems, conversion-efficiency related properties of the QD wafers, which are the key enabling element of the novel system, should be systematically studied. In general, there are two essential parameters of a PCA substrate that are responsible for the efficiency of THz generation – the wafer photoconductivity as a function of pump wavelength and the lifetime of the photoexcited carriers.

Photoconductivity of the QD materials has been extensively studied in the mid- [22]–[25] and even far- [26] IR spectral range, where it occurs due to intersubband transitions at lower temperatures, with the interest in using such materials as mid-IR cryogenically cooled sensors. Also, QDs were demonstrated to enhance the performance of solar cells [19] by broadening their operational spectrum from visible to IR. However, to the best of our knowledge there has been no specific interest in interband photoconductivity studies. Some works reporting research on IR QD photoconductivity, had been published earlier [25], [27]–[31], but with a different focus, on different samples and pump/bias conditions.

In this paper, we report a study of the InAs/GaAs QD PCA photoconductivity spectral response in the operational band of a compact broadly-tunable semiconductor laser utilising a gain medium containing similar InAs/GaAs QDs. The choice for the pump source used in the study was motivated by the promising results of THz generation demonstrated from a similar system [5].

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II. Sample growth and antenna fabrication

The InAs/GaAs QD PCA structures were grown by molecular beam epitaxy (MBE) in the Stranski-Krastanow regime on an undoped GaAs substrate. The general layout of QD structures used for THz photoconductive antennas is shown in the inset of Fig. 1(a). The structure contained 40 equally spaced layers of InAs/GaAs QDs, and the QDs sizes were precalculated to have the ground state, the first and the second excited states at 1218 nm, 1158 nm, and 1141 nm, respectively. The photoluminescence spectrum of the structure is shown in Fig. 1(a).

To ensure the uniformity of the QD layers, each of them was grown by deposition of 2.3 monolayer (ML) InAs at 500° C, capped by 4 nm of $In_{0.15}Ga_{0.85}As$, and 6 nm GaAs afterwards. Then the temperature was raised to 580° C in order to desorb segregated In, and only after that, the subsequent 30 nm GaAs spacer layer was grown. Prior to the growth of each QD layer, the GaAs surface was annealed under an As_2 flux for 5 minutes to flatten the surface. The Atomic Force Microscope (AFM) analysis of the structure gave an estimate of the QD density of about 3×10^{10} cm^{-2} per layer.

The operating wavelengths of the QD active part of the PCA were selected to fall into the operation band of previously demonstrated compact ultrafast semiconductor lasers [9]. The PCA wafer structure also had a 30 nm top layer of LT-GaAs. This layer is very thin (in comparison with the ~ 1.4 μm thick active region), and thus its influence on the conductivity and lifetimes of the sample is negligible. The purpose of this layer is to increase the dark resistance and allow for better contact with metallic PCA electrodes. An extra spacer layer of GaAs was grown under the active photoconductive region on an AlAs/GaAs Distributed Bragg Reflector (DBR) of 30 layers. The need for the DBR is two-fold: to reflect the pump beam thus reducing the IR power at the antenna output, and to allow the possibility for full optical cavity-type optimization of the structure [20].

The fabrication of a metallic antenna over a semiconductor substrate was done using a standard UV photolithography and wet etching of the surface Ni/Au (40-nm/200-nm, respectively) features, and a post-process annealing to increase Ohmic contact between the antenna metal and the LT-GaAs surface. The antenna used in this experiment had a coplanar stripline design with a photoconductive gap of 50 μm and an overall contact thickness of 240 nm (Fig. 1 (b)). Similar PCAs were previously used for the generation of pulsed [6] and CW [5] THz radiation.

III. Experimental setup

In this work, InAs/GaAs self-assembled QD structures similar to those described in ref. [15], [32] were used for the fabrication of a laser chip. The experimental setup layout is shown in Fig. 1 (b). The core element of the laser pump source consisted of an InAs/GaAs QD laser diode with an active region containing 10 non-identical layers of InAs QDs grown on a GaAs substrate by MBE in the Stranski-Krastanow mode. The laser chip ridge waveguide had a width of 5 μm and a length of 4 mm, and was angled at 5° with respect to the normal of the back facet. Both laser chip facets had conventional anti-reflective (AR) coatings with total estimated reflectivity of 10^{-2} for the front facet and less than 10^{-5} for the angled facet. The laser chip was mounted on a copper heatsink with its temperature controlled by a thermo-electric cooler. The laser was set up in a quasi-Littrow configuration, similar to that reported in [32]. In this configuration, the radiation emitted from the back facet of the laser chip was collected with an AR-coated 40x aspheric lens (numerical aperture of 0.55) and coupled onto a diffraction grating (1200 grooves/mm), which reflected the first order diffraction beams back to the laser chip. Wavelength tuning was achieved by rotating the diffraction grating to select the wavelength of the light reflected back to the laser chip. The laser output was monitored using an optical spectral analyzer (OSA Advantest Q8383) with the resolution of 0.1 nm and a broadband thermopile power meter. With this laser, broad tunability of 182 nm (between 1128 nm and 1310 nm), at room temperature (20° C) and an operation current of 1.7 A giving a maximum output power of 435 mW, was achieved [5].

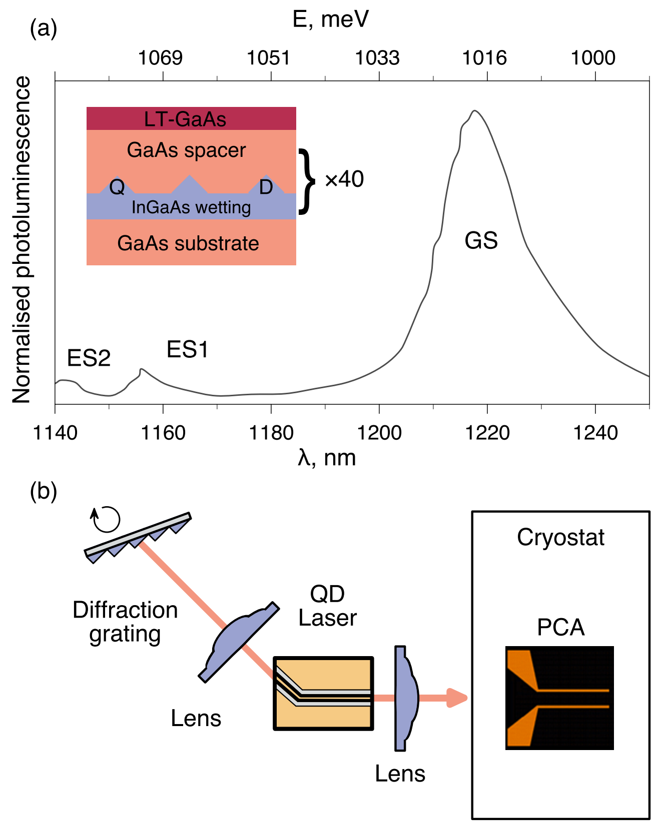

Fig. 1. (a) Normalized photoluminescence spectrum with the ground state (GS), the first excited state (ES1) and the second excited state (ES2) indicated; (b) the simplified schematic of the experimental setup. Inset: QD PCA substrate layout.

This broadly-tunable laser was used for pumping the InAs/GaAs QD PCA in CW single wavelength regime to excite photocarriers and study the wavelength dependence of this process. Due to the use of a cryostat in our experiments which affected the ambient temperature, the laser tunability range was limited on the shorter wavelength side. Nevertheless, the laser operating range covered the wavelengths of interest – the InAs/GaAs QD ground state (GS) and excited states (ESs). The laser was tuned in the range between 1140 nm and 1250 nm, with its bias current adjusted between 0.9 A and 1.6 A to keep the output laser optical power within the same order of magnitude for all wavelengths (20 mW – 100 mW).

To investigate the photoconductivity of the QD antenna at temperatures ranging from 13 K to 400 K under high vacuum ($\sim 10^{-7}$ torr), the antenna was mounted on a copper holder inside a closed cycle Helium based cryostat "Janis CCS-450". Portable probes were used to make an electrical connection with the bond pads of the QD antenna. Next, to record the photo current at all excitation wavelengths, a semiconductor charaterization system "Keithley 4200 SCS" was used to apply a DC voltage sweep from –20 V to +20 V at all temperatures corresponding to the field values of –4 kV/cm to +4 kV/cm inside the antenna gap.

IV. Experimental results and discussion

During the experiment, at all temperatures the PCA was kept at similar pressure conditions under vacuum in the cryostat at all temperatures. The cryostat had a quartz window that allowed for the 90% transmission of the laser pump.The pump radiation was collected into the PCA gap with an AR-coated plano-convex lens with the focal length of 100 mm, and the resulting spot fully covered the gap, resulting in the optical power density not higher than $8\ \mathrm{kW \cdot cm^{-2}}$. Position of the pump spot was tuned to achieve the minimum antenna resistance.

At each temperature under the investigation, the laser was gradually tuned within the 1140 nm – 1250 nm spectral range, with its bias current adjusted to keep the output power within the specified limits as mentioned above. The I-V curves from the laser pumped PCA were recorded for every pump laser wavelength. To distinguish photoinduced currents from thermally excited ones, similar I-V curves were recorded for the unpumped antenna and subsequently subtracted from the photoconductivity curves.

Photoconductivity spectra of the QD based PCA at different temperatures are shown in Fig. 2 The presented spectra correspond to the antenna biased with 20V DC, which corresponds to the electric field of 4kV/cm across the gap. All spectra reveal distinct peaks, clearly corresponding to the GS, ES1, and, for higher temperatures, when the energy falls within the laser operational range, the ES2.

Analyzing the dependence of the ground and first excited state photocurrent peaks on temperature (Fig. 3 (a)), we find that, while neither of them can be described perfectly by a single activation energy (which is not surprising, since the photocurrent is governed by interrelated processes of interlevel relaxation and carrier escape, and the energy separations between levels are themselves somewhat temperature dependent), the ground state peak amplitude can be fitted reasonably well by an activation type curve with an activation energy of ~ 65 meV. This value is greater than the energy separation between the ground state and the first excited state

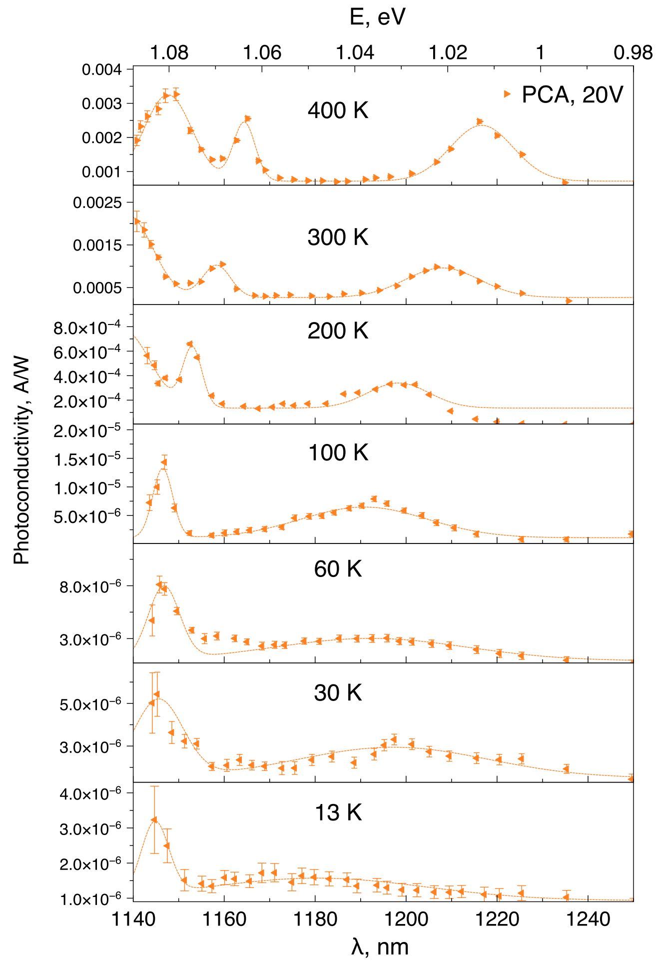

Fig. 2. Photoconductivity spectra of PCA biased with 20V DC, at various temperatures. Solid curves represent fitting with three (two for lower temperatures) gaussians, corresponding to GS and ES QD PCA photoconductivity peaks.

(~ 52 meV at room temperature) but appears to be quite close to that between the ground state and the second excited state (~ 68 meV at room temperature), particularly given the significant error bar in extracting the activation energy. This indicates that thermal activation from the ground state to the excited states (particularly the upper one), with subsequent fast escape, plays a significant part in the carrier kinetics determining the photocurrent. The temperature dependence of the lower excited state peak can be reasonably well described by a thermal activation energy of ~ 55 meV down to temperatures of ~ 80 K. Below that, the temperature dependence saturates, indicating direct tunneling of carriers in the applied electric field from this relatively shallow level as the main escape mechanism at low temperatures.

The rising photocurrent at higher temperatures and even more pronounced peaks suggest that, in accordance with previous measurements of THz generation from similar PCAs, these antennas can operate without saturation up to the highest pump intensities studied here, and further research is needed to reveal the limitations and intensity levels leading to sat-

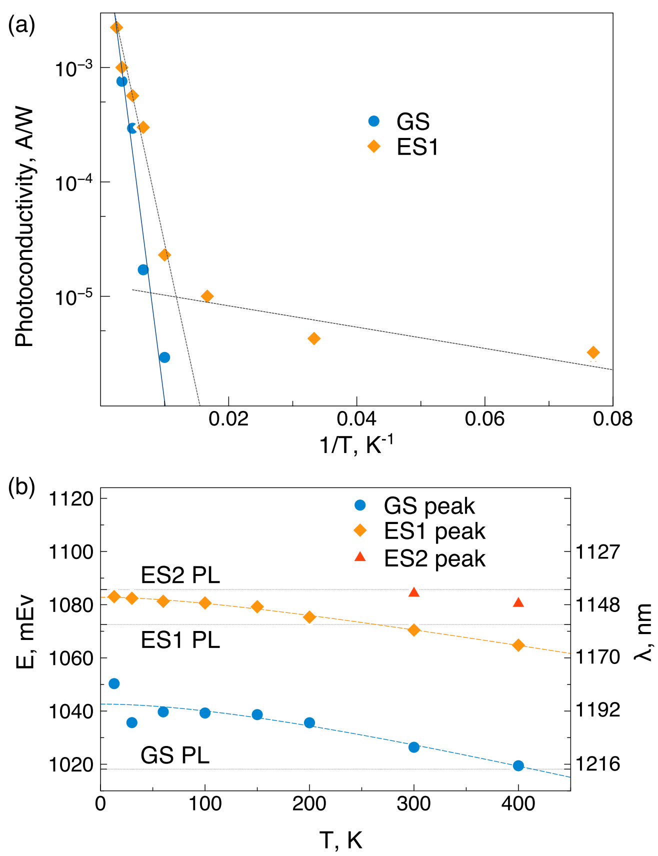

Fig. 3. (a) GS and ES1 Photoconductivity dependence on inverse temperature. (b) Temperature dependence of GS, ES1 and ES2 photoconductivity peaks. Dashed lines show Varshni relation approximation for the data.

uration. Similarly, an application of higher external electric fields yields higher, yet resonantly dependent on the pump photon energy, photocurrent, and the precise pump wavelength selection is still the key enabling factor for the efficient carrier excitation. However, significantly higher electric fields, potentially available by using dielectric substrates instead of SI-GaAs under an active region [33], may result in Stark shifts of conductivity peaks, previously reported even at elevated temperatures [29].

A blue shift in the GS photoconductivity peak with temperature, similar to the one observed by us, was previously reported in [29], [34]. As can be seen from Fig. 3 (b), the temperature dependence curves of the GS, ES1 and ES2 photoconductivity peaks cross the room-temperature PL values at (ES1, ES2), or below (GS curve), the room temperature and follow the Varshni relation for bandgap [35]. Taking into account the similar temperature dependence of PL peaks [36], one can expect the temperature-dependent positions of the PL and photoconductivity peaks (in the absence of strong extrinsic or intrinsic electric fields) to coincide reasonably closely. Hence, the PL peaks can give a clue for the best operating pump wavelengths for the PCA.

Persistent photoconductivity under pump wavelengths longer than 1120 nm [37] has been reported at lower temperatures, but to the best of our knowledge no investigation of the nature of carrier extraction and its variation with temperature has been reported. The results look promising for THz applications. Indeed, carrier generation and capture processes in these THz QD wafers at room temperatures are known to be fast enough to allow for the efficient generation of pulsed THz radiation [6], as carrier lifetimes below 1 ps are needed and have previously been reported [13], [38]. Importantly, the picosecond photoconductivity may differ from that under the CW pump [39], so further experimental and theoretical work is in order.

V. Conclusion

In conclusion, we presented a detailed study of the IR photoconductivity in self-assembled InAs/GaAs quantum dots. A compact semiconductor QD laser was used as a narrowband coherent pump source. We have demonstrated the temperature dependence of the photoconductivity spectra. The positions and strengths of the photoconductivity peaks were found to depend only on temperature; no spectral shifts due to an external electric field were observed. At temperatures below 80 K, the GS photoconductivity is gradually vanishing, but the ES photoconductivity persists. This effect is qualitatively explained by different dominating mechanisms of carrier extraction for these pumping conditions. The measured photoconductivity peaks are slightly blue-shifted with respect to the PL peaks at room temperature, and have no resemblance to the latter as regards the amplitude ratio. The distinctive peaks in the conductivity spectrum correspond to the same in the sample PL spectrum, which makes it possible to rely on the PL data when selecting the optimal pump laser source. The presence of such peaks confirms the promise of such QD based photoconductive wafers as substrates for efficient THz generators in the 1 – 1.3 μm pump wavelength range. The underlying carrier extraction mechanisms offer a plausible explanation for the absence of THz generation at GS pump wavelengths, reported earlier [6].

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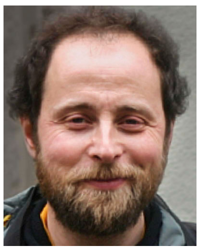

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