Effect of Quantum Dots Density on Response Time of Photodetectors Fabricated from Quantum Dots Deposited on Porous Indium Arsenide Layers

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Abstract
In this work, the effect of quantum dots (QDs) density prepared on porous indium arsenide (InAs) layer grown on silicon substrates was studied. Pulsed-laser deposition was used to prepare the QDs while the Photoelectrochemical etching technique was used to form the porous InAs layer on the silicon substrate. The density of the QDs was found very influential on the shortening of the response time of the photodetectors fabricated from the multilayer structures. The shortest response time achieved was 55µs for QDs density of 10^4 /mm^2.

Keywords: Silicon devices; Indium arsenide; Quantum dots; Photodetectors
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1. Introduction

Photodetectors are essential components in a wide range of applications, including optical communication, environmental monitoring, and biomedical sensing. The response time of a photodetector—defined as the time it takes for the device to detect and register a change in incident light—is a critical parameter that directly impacts its performance. Photodetectors with shorter response times are crucial for high-speed applications, such as data transmission and real-time imaging.

Quantum dots (QDs) and porous substrates have garnered significant attention for their ability to improve the performance of photodetectors. In particular, quantum dots, due to their tunable electronic and optical properties, enable efficient light absorption and carrier generation. When these are combined with a porous indium arsenide (InAs) substrate, the unique structural and electronic properties of the substrate further enhance the photodetector's performance. This article delves into the strategies and mechanisms employed to shorten the response time of photodetectors fabricated from QDs deposited on porous InAs substrates, emphasizing the fabrication process, material optimization, and design considerations.

Quantum dots are nanoscale semiconductor particles that exhibit quantum confinement effects, which allow their optical and electronic properties to be tuned by changing their size and composition. This makes them ideal for enhancing photodetection across a wide spectral range. Indium arsenide (InAs) is a III-V semiconductor with a narrow bandgap and high electron mobility, making it an excellent material for infrared photodetectors. When InAs is made porous, its surface area increases significantly, providing more sites for quantum dot deposition and improving light absorption and carrier generation.

The porous InAs substrate also introduces unique optical and electronic properties. The porous structure reduces the refractive index mismatch between the substrate and air, minimizing reflection losses and enhancing light trapping. Furthermore, the increased surface area and porosity facilitate better quantum dot adhesion and distribution, which are crucial for efficient carrier transport. This synergistic combination of quantum dots and porous InAs creates a platform for high-performance photodetectors with enhanced responsivity and reduced response time.

Photodetectors with shortened response times have significant potential in various high-speed and real-time applications, including optical communications as high-speed photodetectors are essential for detecting optical signals in fiber-optic communication systems, enabling faster data transmission rates. Ultrafast imaging using real-time imaging systems, such as those used in biomedical diagnostics or industrial inspection, require photodetectors with rapid response times to capture transient events. They are also used for lidar technology for autonomous vehicles and remote sensing relies on high-speed photodetectors to accurately measure light reflected from objects. Photodetectors are efficiently used for the time-resolved spectroscopy. Scientific research applications, such as fluorescence lifetime imaging and ultrafast spectroscopy, benefit from photodetectors with ultrafast response times to detect transient optical signals with high precision.

In this work, integrating quantum dots with porous InAs layer on silicon substrates is presented to achieve significant advancement in developing photodetectors that meet the growing demands for ultrafast, efficient, and reliable performance.

2. Experimental Part

The fabrication process is critical to achieving a photodetector with a short response time. A step-by-step outline of the typical fabrication process is presented. Porous InAs is typically fabricated through electrochemical etching, where the InAs substrate is immersed in an electrolyte solution (e.g., hydrofluoric acid or sulfuric acid) and subjected to an applied current. The porosity and pore size can be controlled by adjusting the etching parameters, such as current density, etching time, and electrolyte concentration. The resulting porous structure provides a high surface area and introduces a network of pathways for carrier transport.

Quantum dots can be synthesized using techniques such as colloidal synthesis or molecular beam epitaxy. For example, lead sulfide (PbS), cadmium selenide (CdSe), or InAs quantum dots can be used depending on the desired spectral response. The size and surface chemistry of the quantum dots are optimized to ensure efficient light absorption and charge carrier generation. The quantum dots are deposited onto the porous InAs substrate using techniques like spin coating, dip coating, or drop casting.

To enhance the adhesion and uniform distribution of quantum dots, surface functionalization of the porous InAs substrate with linker molecules (e.g., thiol or amine groups) can be employed.

Metal electrodes are deposited on the quantum dot-coated porous InAs substrate using techniques such as thermal evaporation or sputtering. A protective encapsulation layer may be added to ensure device stability.

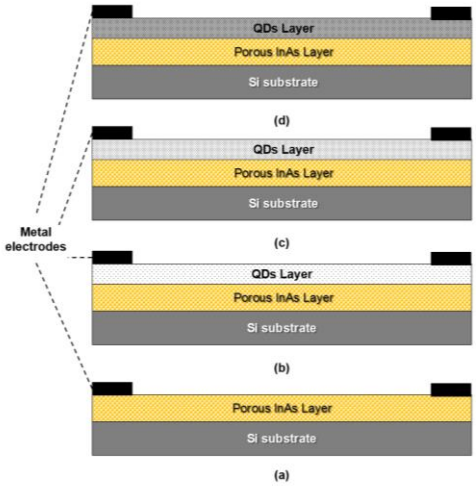

Fig. (1) Structures of the fabricated photodetectors (a) as-prepared porous InAs/Si, (b) QDs density of 100 /mm^2, (c) 1000 /mm^2, (d) 10000 /mm^2

3. Results and Discussion

The response time of a photodetector is influenced by several factors, including carrier generation, transport, and recombination dynamics. One of the key mechanisms involved in shortening the response time is the efficient carrier generation. The quantum dots absorb incident photons and generate excitons (electron-hole pairs). Due to the quantum confinement effect, the absorption can be tuned to match the incident light's wavelength. The porous InAs substrate further enhances light absorption by trapping light within its structure, increasing the probability of photon absorption. Another mechanisms involved in shortening the response time is the rapid carrier separation. After generation, the excitons must be efficiently separated into free electrons and holes to contribute to the photocurrent. The heterojunction formed between the quantum dots and the porous InAs substrate provides an electric field that facilitates this separation.

Third mechanisms involved in shortening the response time is the reduced carrier transit time. The porous structure of InAs introduces a network of interconnected pathways, reducing the average distance that carriers must travel to reach the electrodes. The high electron mobility of InAs ensures that the carriers travel quickly through the substrate, minimizing transit time.

Fourth mechanisms involved in shortening the response time is the minimized carrier recombination. Surface passivation of quantum dots and porous InAs can reduce surface trap states, which are common sites for non-radiative recombination. Proper surface functionalization and encapsulation layers can further minimize recombination losses, ensuring that a larger fraction of generated carriers contribute to the photocurrent.

To achieve an ultrafast response time in quantum dot-based photodetectors on porous InAs substrates, the following strategies can be employed. Optimizing quantum dot properties by controlling the size and composition of quantum dots to ensure strong light absorption and rapid exciton dissociation. Using core-shell quantum dots to reduce surface defects and improve carrier lifetimes.

Enhancing interface engineering may be considered to achieve an ultrafast response time in quantum dot-based photodetectors on porous InAs substrates. Functionalizing the porous InAs surface with linker molecules to improve quantum dot adhesion and electronic coupling. Creating a graded interface between quantum dots and porous InAs to reduce energy barriers and enhance carrier transport.

Improving porous InAs morphology may lead to achieve an ultrafast response time in quantum dot-based photodetectors on porous InAs substrates. Fine-tuning the etching parameters to achieve an optimal pore size and distribution that balances light trapping and carrier transport. Ensuring structural stability of the porous InAs to prevent degradation under operating conditions.

Reducing parasitic capacitance and resistance can result in an ultrafast response time in quantum dot-based photodetectors on porous InAs substrates. Minimizing the series resistance of the device by using high-conductivity electrodes and ensuring good electrical contact. Reducing parasitic capacitance by optimizing the device geometry and using dielectric layers where necessary.

Advanced fabrication techniques can be used to achieve an ultrafast response time in quantum dot-based photodetectors on porous InAs substrates. Employing atomic layer deposition (ALD) or molecular layer deposition (MLD) to achieve conformal coatings of quantum dots on porous InAs. Integrating high-speed readout circuits to minimize the electronic bottleneck in response time.

The response time of the fabricated photodetectors shown in Fig. (2) can be experimentally evaluated using the following methods. Time-resolved photocurrent measurements (Fig. 3) in which, a pulsed light source, such as a laser or LED, is used to illuminate the photodetector, and the photocurrent is measured using an oscilloscope or fast measurement circuit. The rise time (time taken to reach 90% of the maximum photocurrent) and fall time (time taken to decay to 10% of the maximum photocurrent) are extracted from the photocurrent waveform.

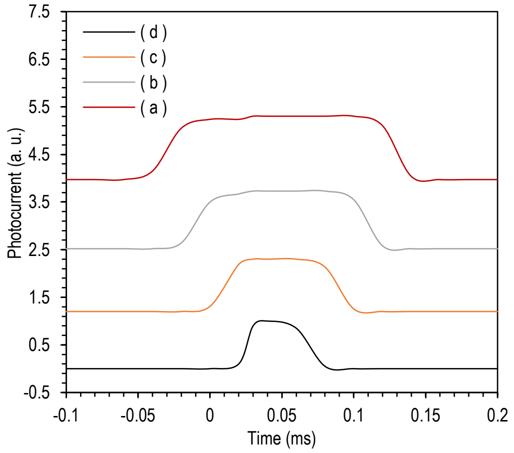

Fig. (2) Variation of response time with the variation of QDs density on porous InAs layer grown on Si substrate (a) as-prepared porous InAs/Si, (b) QDs density of 100 /mm^2, (c) 1000 /mm^2, (d) 10000 /mm^2

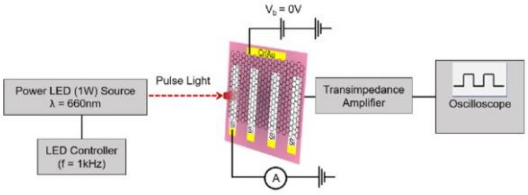

Fig. (3) Experimental setup for the time-resolved photocurrent measurements of response time for the fabricated photodetectors

The photodetector’s frequency response is measured using a modulated light source, and the cutoff frequency is determined as the frequency at which the response drops to 3 dB below the maximum. The response time is inversely related to the cutoff frequency.

The pump-probe spectroscopy can also be used to assess the rise time of the photodetectors. This technique involves using an ultrafast laser to excite the device (pump) and a delayed probe pulse to measure the carrier dynamics. The carrier lifetimes and recombination rates can be extracted, providing insights into the factors limiting response time.

4. Conclusion

In conclusion, the effect of quantum dots (QDs) density prepared on porous indium arsenide (InAs) layer grown on silicon substrates was studied. The density of the QDs was found very influential on the shortening of the response time of the photodetectors fabricated from the multilayer structures. The shortest response time achieved was 55μs for QDs density of 10^4 /mm^2.

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