Fabrication and Characterization of CTS Quantum Dots Based Hybrid Structures for Broadband Photodetection

Thesis submitted in partial fulfilment for the

Award of Degree

Doctor of Philosophy

By

Sanjeev Mani Yadav

DEPARTMENT OF ELECTRONICS ENGINEERING

INDIAN INSTITUTE OF TECHNOLOGY

(BANARAS HINDU UNIVERSITY)

VARANASI - 221005

(INDIA)

Roll No: 17091004

2021

Chapter 6

CONCLUSION AND FUTURE WORK

In this chapter, we have concluded and summarized the overall research work done in this thesis and the importance of our findings for broadband photodetection applications. We have further summarized the future scope as well as the future work in this chapter

6.1 Introduction

The objectives of the present thesis is to investigate the broadband photo-conductors based on solvothermal processed 0D-CTS QDs and their hybrids with 2D-graphene and 2D-SnS_2 nanoflakes. Initially, the simplest device structure Ag/CTS QDs/Ag with small channel separation for the Vis-NIR band is realized. The CTS QDs structures have been investigated for the first time with photoconductor geometry and its superiority over other widely used broadband (Vis-NIR) QDs structures like PbS, PbSe, HgTe, CdTe, etc., in terms of broad range absorption, high absorption coefficient, nontoxic, earth-abundant and more stable geometry is established.

In the second phase, the optical performance of the Ag/CTS QDs/Ag structure has been improved by realizing its hybrid structure with 2D-layered graphene, a high mobility material synthesized by CVD technique. The performance of the 2D/0D Graphene/CTS QDs hybrid photoconductor has been investigated by measuring the responsivity, detectivity, EQE, etc., of the device for the broad Vis-NIR range. The realized structure has improved these parameters efficiently by utilizing the ultra-high carrier transport property of graphene compared to the stand alone CTS QDs film structure .i.e., Ag/CTS QDs/Ag.

The limitation of low absorption of graphene (∼2.3 %) for broadband spectrum further extends our study to explore some other classes of 2D-materials with high absorption coefficient along with good carrier mobility. Thus, 2D-SnS_2, a layered TMDs material has been explored due to its large bandgap tunability, high absorption coefficient, high stability, non-toxic, earth-abundant properties. Therefore, the photoconductor structure of low-cost one pot solvothermal synthesized SnS_2 nanoflakes has been realized and explored for broadband illumination. The observed optical performance of Ag/SnS_2 nanoflakes /Ag-based structure shows its potentiality over the UV band while the optical response is poor in visible to NIR range.

Finally, the bandwidth of Ag/SnS_2 nanoflakes/Ag photoconductor has been extended to Vis-NIR band also by utilizing the hybrid structure (2D/0D) of SnS_2 nanoflakes and CTS QDs resulting in an UV-Vis-NIR broadband photodetector. The realized broadband photodetector involves both active materials i.e., CTS QDs and SnS_2 nanoflakes, which have been synthesized by low-cost solvothermal technique and results in a low-cost hybrid structure over CVD grown graphene-based hybrid structure. Apart from the low-cost design of the 2D/0D SnS_2/CTS QDs based hybrid structure this structure provides bandwidth extension as well as improved optical performance compared to the previously realized Ag/SnS_2/Ag and Ag/CTS QDs/Ag-based structures in term of responsivity, detectivity, EQE, etc.

In this chapter, we have summarized the major observations presented in various chapters of the thesis. We have also tried to outline some scopes for future work related to the area considered in the present thesis. The thesis is summarized chapter-wise as following.

6.2 Summary and Conclusion

Chapter-1 represent the basics of photodetection theory includes absorption process and photo-generation mechanism in photodetector structure. Further various traditional broadband photodetection structure and their performance has been discussed briefly. The section also includes the discussion on the superiority of photoconductor structure over other available detection structures due to its simplest design. The limitation of the traditional materials-based broadband photodetection has been discussed in this section and explored a new class of materials. This chapter also brief the nanomaterials and their superiority over traditional materials. Various nanostructure geometry like 2D, 1D, 0D has been discussed in this chapter and then a focused study on 0D and 2D nanostructure is given. In the latter half of this chapter, some states of artwork on the 0D QDs structures used for broadband photodetection has been reviewed. Out of many QDs structures for broadband applications CTS and its QDs structure have been explored due to its favourable optoelectronic properties. In the same chapter the state of artwork on graphene and SnS_2 based broadband photodetection and their hybrid with QDs has been studied. Finally, from the literature review of CTS QDs, 2D-graphene and 2D-SnS_2 based photodetection structures, the simple and hybrid (2D/0D) photoconductor structures of these materials has been proposed for broadband photodetection.

Chapter-2 reports a solvothermal processed CTS QDs based photoconductor structure for Vis-NIR illumination. The CTS QDs are simply drop cast over a small spaced electrode about ∼63.3 micrometers to realize an Ag/CTS QDs/Ag photoconductor structure. The performance of the structure has been summarized as follows.

- This chapter reports a photoconductive type (Ag/Cu_2SnS_3(CTS) QDs/Ag) Vis-NIR photodetector having small channel spacing (∼63.3µm) on glass substrate
- The low cost solvothermal processed CTS QDs have been used as carrier transporter as well as broad light absorber.
- The optical parameters of the proposed structure for small illumination power density have been calculated for broad range light illumination wavelengths (650-1100 nm).
- The responsivity of device was found to be ∼37 (mA/W) for visible (730 nm) and ∼67 (mA/W) for NIR (940 nm) illumination wavelengths.
- The sensitivity of the device was observed to be ∼2.3 and ∼8.2 for 730 and 940 nm illumination wavelengths, respectively, at 5V.
- The time response of the device have been measured under Vis-NIR illumination and found to be 0.96 s (rise time) and 1.29 s (fall time)

Chapter-3 is the improvement of the limitation of the colloidal QDs film mobility which degrades the performance of the structure for Vis-NIR photodetection by employing a high mobility material called graphene. The high-quality large-area CVD-grown graphene also provides a high conducting channel for the photo carriers generated in CTS QDs and enhances the optical performance for Vis-NIR illumination. The hybrid structure of CTS QDs with graphene has been studied in this section with improved photodetection characteristics of the CTS QDs based structure discussed in Chapter-2. The optical performance of Graphene/CTS QDs hybrid broadband structure is summarized below.

- The fabrication of a broadband hybrid 2D/0D visible-near infra-red response (Vis-NIR) photodetector using Cu_2SnS_3(CTS) quantum dots (QDs) as photoactive semiconductor material and graphene as a carrier transport medium.

- The CVD-grown graphene is used to fabricate the CTS QDs/Graphene hybrid PD structure.

- The fabricated CTS QDs/Graphene/SiO_2/Si PD demonstrated high values of responsivity (∼110.089 A/W), detectivity ($\sim 1.25\times10^{12}$ cm $Hz^{1/2}W^1$), and quantum efficiency (∼160.9) for broadband (Vis-NIR) region due to high absorption coefficient of CTS QDs and high mobility of graphene.

- The time-response analysis of PD was also performed under vis-NIR and ON and OFF time were found to be 10.2 and 11.34 s.

- The applications of the device may be found in optical communication, solar cell, in thermal imaging, remote sensing, and in the field of bio-sensing.

Chapter-4 reports a photoconductor structure based on one-pot solvothermal synthesized SnS_2 nanoflakes materials, a TMDs family 2D-layered material to overcome the low absorption of graphene under the broad light illumination. The low absorption of graphene further enhances the overall cost of the structure by involving the costly CVD technique as discussed in Chapter-3. The realized structure Ag/SnS_2 nanoflakes/Ag has been studied under broad light illumination. The proposed structure shows efficient optical performance in UV regions while it starts degrading in the visible and NIR region due to low absorption of SnS_2 nanoflakes. The optical performance of an efficient UV band simplest device structure is summarized below.

- This chapter reports the fabrication and characterization of SnS_2 nanoflakes based UV photodetector. SnS_2 nanoflakes have been synthesized by using solvothermal technique.

- The fabricated SnS_2 nanoflakes/SiO_2/Si photodetector offers high contrast ratio (400), high responsivity (5.5 A/W) and detectivity (1.72×10^{13} Jones) under UV light illumination.

- The temperature based ln(I)-V characteristics analysis of photodetector was also performed for the range of 60 ^{o}C to 120 ^{o}C to confirm the thermal stability of the device.

- Furthermore, the response time of our fabricated device under UV irradiation was found to be around 2.2 s.

- The fabricated UV detector may have variety of applications in health monitoring, bio-sensing, UV spectroscopy, and flame detection etc., due to it's simple, and cost-effective fabrication.

Chapter-5 reports the bandwidth enhancement as well as the improvement in the optical characteristics of the structure discussed in earlier chapters via the low-cost hybrid structure design of solvothermal synthesized active materials i.e., CTS QDs and 2D-SnS_2 nanoflakes. The fabricated 2D/0D SnS_2 nanoflakes/CTS QDs photoconductor in this chapter have improved the overall performance of the device structure compared to the structures discussed in Chapter-2, 3, and 4 along with an extension of light detection from UV to NIR region. The optical performance of the fabricated 2D/0D SnS_2 nanoflakes/CTS QDs are summarized below.

- This chapter reports the SnS_2 nanoflakes/Cu_2SnS_3 CTS QDs-based hybrid ultra-wide band photodetector (PD). The fabricated device detects the illumination in the 300–1100-nm spectrum (UV–Vis–NIR).

- The synergetic effect of UV detection characteristics of SnS_2 nanoflakes and NIR detection characteristics of CTS QDs is utilized to obtain ultra wide-band detection in the UV to NIR region.

- Low cost and simple solvothermal technique has been used to synthesize good quality of 2D SnS_2 nanoflakes (size ∼146 nm) and 0D CTS QDs (size, ∼3.2 nm)

- In addition to being an active semiconductor for UV light, the SnS_2 nanoflakes layer in the device has an additional task of being a carrier transport layer for the photogenerated carriers in CTS QDs.

- The sensitivity of the fabricated CTS QDs/SnS_2 nanoflakes-based PD was found to be 296.2, 240.7, and 368.05 for illumination wavelengths of 320, 640, and 970 nm, respectively.

- The reported CTS QDs/SnS_2 nanoflakes-based 2D–0D hybrid detector has a responsivity of 53.88, 5.16, and 12.61 A/W for 320, 640, and 970-nm light wavelengths, respectively, and best detectivity has been observed in the order of 10^{13} Jones for UV light

6.3 Future Scope of the Thesis

This thesis presents some investigation on the optical characteristics of CTS QDs and their simple and hybrid photoconductor structures with 2D-graphene and 2D-SnS_2 nanoflakes for broadband photodetection applications. Based on constraints and limitations of the works carried out in this thesis, here some future scope are given below:

- Colloidal core/shell structure of CTS QDs can be explored to further extend the absorption from Vis-NIR to UV-Vis-NIR.

- The strong optical characteristics of hybrid CTS QDs structures for visible band can be explored in the field of solar cell applications.

- The hybrid structure of CTS QDs with graphene can be explored with various 2D-substrates like h-BN having perfect lattice match with graphene to study the scattering effect and its consequences on the optoelectronic properties of device.

- The hetero-junction analysis of the 0D-QDs and 2D layered materials can be carried out to further investigate the optoelectronic properties of these device.

- New type of hybrid structures of CTS QDs with ultra high carrier mobility and non zero-band gap nanostructures like 1D nanorods could also be explored at nanoscale fabrication level by employing lithography techniques.