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InP-based Sb-free Lasers and Photodetectors in 2-3 µm Band

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Abstract

Zhang et al. efforts on the explore of InP-based Sb-free 2-3 µm band lasers and photodetectors are introduced, including the 2-2.5 µm band type I InGaAs MQW lasers under pseudomorphic triangle well scheme, 2.5-3.0 µm band type I InAs MQW lasers under metamorphic strain compensated well scheme, as well as InGaAs photodetectors of high indium contents with cut-off wavelength large than 1.7 µm. All device structures are grown using gas source MBE method, and CW operation above room temperature have been reached for the lasers with wavelength less than 2.5 µm. Pulse operation of 2.9 µm lasers at TE temperature also have been reached The dark current of 2.6 µm InGaAs photodetectors have been decreased notably with the inserting of supperlattice electron barriers, those types of epitaxial materials have been used to the development of FPA modules for space remote sensing applications.

Keywords: Semiconductor lasers; Photodetectors; InP-based; Sb-free; Gas source MBE

Introduction

Semiconductor lasers and photodetectors in the 2-3 µm band have many important applications in numerous areas, such as satellite remote sensing, gas detection, night and fog penetrating vision, eye-safe wind-detecting lidar, spectral and medical instrumentations, as well as free-space light communications. Figure 1 shows main applications of the short-wave infrared band in satellite remote sensing, as well as absorptive features of water vapor and carbon dioxide. This paper introduces our works on the lasers and photodetectors in this band.
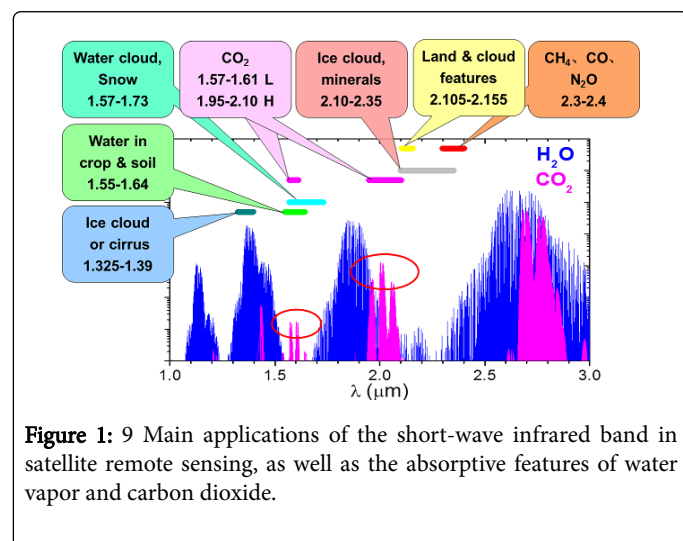

Figure 1: 9 Main applications of the short-wave infrared band in satellite remote sensing, as well as the absorptive features of water vapor and carbon dioxide.

For semiconductor lasers, in principle antimonide type-I quantum wells on GaSb substrate may cover the 2-3 µm band primely, the

difficulties are on the extending of the lasing wavelength even longer and fulfill the performance demands at room temperature (RT). Efforts have been made in previous years [1-3], and their applications are explored [4-6]. However, antimonide containing materials are suffered from some essential or technical problems, such as the existence of miscibility gap and therefore the difficulties in epitaxial growth. The Sb source in the growth is not so compatible with other sources and the device processing is still not mature. Also, the thermal conductance of antimonide is poor, and the price of GaSb substrate is high. Furthermore, to reach a better confinement, in those type-I antimonide laser structures high Al content materials are often adopted, especially for longer wavelength. Because of the high chemical activity of pure Al, the introducing of high Al containing materials into laser structure are considered harmful to the reliability, this have been confirmed in the early work of AlGaAs/GaAs lasers. Therefore, even some successful reports of the lasers and other types of device adopting high Al (Al > 70%) or even pure Al (such as AlAs and AlSb) materials could be found, in this case the surface and side protection and passivation in both growth and processing steps should be very critical, as well as the punch through defect and pin-hole densities. The long-term reliability data is still rare, especially for the devices with high local power density as lasers.

Besides, the interband cascade lasers (ICL) of antimonide [7,8] and antimonide containing inter-subband quantum cascade lasers (QCL) [9], which works well at longer wavelength, are extending their wavelength to short wavelength side, lasing wavelength below 3 µm have been reported [10]. For those types of lasers, the design space will be limited when extending to shorter wavelength, as well as the performances. The GaSb-based antimonide lasers adopting type-II quantum wells or cascaded type-I wells may also worked in 2-3 µm band, and CW operation at room temperature have been reported [11-13]. For those lasers, antimonide in combination of type-II band alignment provide a distinctive degree of freedom in design, the tailoring of the lasing wavelength is more effective. Of course, the

problems of antimonide, high Al containing materials and GaSb substrate are still need to be confronted. The lattice constant of InAs is close to that of GaSb (only 0.6% difference), so in principle InAs also could be used as substrate for those lasers, and its price in lower than GaSb. Lasers with well performance have been reported [14,15], but the lower bandgap, melting point and mechanical strength of InAs is detrimental to epitaxial growth and device processing.

Keep away from the problems of antimonide, extending the wavelength of mature InP-based lasers of communication band to long side have been explored [16]. Those lasers are composed of Sb-free ternary InGaAs, InAlAs and quaternary InGaAsP and InAlGaAs materials lattice matched to InP substrate, and adopting type-I quantum wells. The Al contents in the constitutive material are around or below 50%, so no processing and reliability problems of high Al device essentially. Besides, the thermal conductance of InP is doubled compared to those of GaSb or InAs; it is beneficial to the laser. For a laser structure, normally the thick layers should be lattice matched, whereas the thickness of lattice mismatched thin layers is limited by the critical thickness. Restricted by the bandgap of the material system, the lasing wavelength was only extending to about 2 μm at long side based on conventional design. Similarly, the InP or GaAs based QCL, which are also Sb-free and have made great success in mid and far infrared band, are difficult to extend towards short wavelength side because of limited band offset. Even if the lasing wavelength near 3 μm has been reported [17], the performance is not as good as device at longer wavelengths.

As a compromise between antimonide and Sb-free structure, InP based laser structure with small quantity of antimonide in the active zone have also been explored, such as the using of AlAsSb to increase the band offset [18,19], or adopting type-II quantum wells [20,21], in which the waveguide or confinement layers are still Sb-free. Those structures could adopting the strong points while overcoming weak points, but the choices of the material system and design space are very limited especially towards short wavelength side.

Based on above considerations, InP-based Sb-free type-I quantum well lasers in 2-3 μm band have been developed [22]. With the increase of the wavelength, those lasers need confront of the common problems of PN junction interband lasers, such as the decrease of gain, enhancement of Auger recombination, etc. Besides, the effects of large strain in the structures need to be remitted through the optimization of the design and processing, including the 2-2.5 μm band InGaAs MQW lasers adopting pseudomorphic non-rectangular quantum well scheme, and 2.5-3 μm band InAs MQW lasers adopting metamorphic strain compensated quantum well scheme.

As for the photodetectors and focal plane arrays similar situations exist. Antimonide InAsPSb or InGaAsSb quaternaries lattice matched to InAs or GaSb substrates could cover the 2-3 μm band well, early works on the explore of PIN type photodetectors have shown fair results [23-25]. However, because of the problems of antimonide those photodetectors are not well developed. Type-II antimonide superlattice photodetectors on GaSb or InAs substrates are developing rapidly and could also be tailored to this band, but the common problems of antimonide still need to be confronted. GaSb or InAs substrates are all conductive, the free-carrier absorption are unsuitable for the development of back illuminated FPA, while remove of the substrate totally increases the difficulties in the processing dramatically.

II-VI MgCdTe material system with variable bandgap has excellent optoelectronic properties and could cover wider wavelength range. Through a long-term development, photodetectors and FPAs with good performances have been developed in long-wave, mid-wave and short-wave infrared bands, whereas those materials are far from robust because of the weak Hg-Te bond, and the growth and processing steps should be at quite low temperature, in addition to the radiation protection and reliability problems for space applications.

Based on similar considerations, a series of InP-based Sb-free photodetectors also have been developed by using ternary InGaAs with higher indium contents as absorption layer, the cut-off wavelength have been extended from above 1.7 μm to 2.9 μm, and the materials have been applied to FPA applications [26]. Consequently, the effects of large lattice mismatch between the absorption layer and substrate need to be remitted through the optimization of the buffer material and scheme. The dark current of the device need to be restrained by using special structures.

Lasers

Scheme I: Pseudomorphic triangle quantum wells

For the interband quantum well lasers, increase of the lasing wavelength means the decrease of the bandgap of well material. In the premise of using InP as substrate and $In_xGa_{1-x}As$ as well material, this could be realized by increase the indium content x. For the device of longer wavelength adequate gain should be maintained by using sufficient well numbers, but the accumulation of the strain and limitation of critical thickness should be solved. In the case of using rectangular wells the indium contents and well numbers are restricted notably. Calculation and experiments shown at the same total strain extent the indium contents and well numbers could be increased by using of triangle shape wells, and therefore lasing at longer wavelengths. In MBE triangle shape wells could be realized by the growth of short period digitally graded superlattice (chirped superlattice) [27,28]. For reach high performance of the laser in this scheme, the total strain contents, quantum well numbers for sufficient gain, as well as the carrier and optical confinement at numerous restriction conditions, should be considered synthetically, trade-off of the parameters and optimization of the structure and processing is needed [29-32]. In this scheme the CW operation of the InP-based Sb-free lasers above room temperature have been reached in 2.0-2.43 μm range [33,34], and above 10 mW CW output power could be obtained from narrow ridge device at RT. Figure 2 shows the typical output characteristics.

Scheme II: Metamorphic virtual substrate strain compensated quantum wells

For longer lasing wavelength the pseudomorphic triangle well scheme will also be limited, in this case the whole laser structure could be constructed above a virtual substrate to release the large strain problem, the virtual substrate is also grown on InP substrate but with lattice constant large than those of InP.

By using this scheme, the photoluminescence (PL) of wavelength large than 3 μm have been observed at RT for quantum wells grown on InP substrate [35], RT-PL of 2.9 μm also have been seen at similar structure grown on GaAs substrate [36], confirmed the validity of the

scheme. Based on this scheme, whole structure of the laser were designed and grown, in which separate confinement hetero-structure and strain compensated active zone are adopted to keep requisite gain for lasing at quite weak confinement on such long wavelengths. The laser reached 2.7 μm CW lasing at 110 K [37-39], and 2.9 μm pulse lasing at 230 K, but with lower power, and RT-CW operation of the laser have not been reached yet. Figure 3 shows the typical output characteristics.
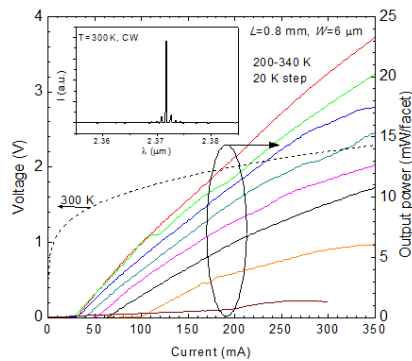

Figure 2: CW Output and I-V characteristics of the InP-based antimony-free lasers at different temperatures under pseudomorphic triangle quantum well scheme, the inset shows its lasing spectrum at RT.
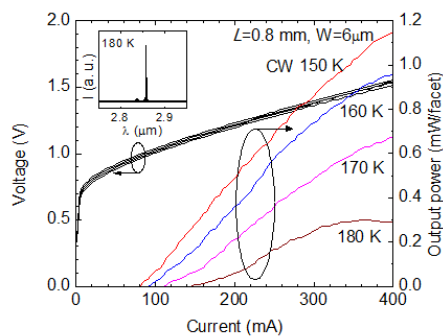

Figure 3: CW Output and I-V characteristics of the InP-based antimony-free lasers at different temperatures under metamorphic virtual substrate strain compensation quantum well scheme, the inset shows its lasing spectrum at RT.

Photodetectors

The contents involved in the research of InP based 2-3 μm band photodetectors including the selection of absorption and buffer layer materials, buffer schemes, grading of hetero-interfaces, suppression of dark current, etc. Considering the particular features of gas source MBE, a series of explore has been taken [40-46]. An optimized structure with high indium $In_xGa_{1-x}As$ absorption layer, linear or step plus linear graded buffer layer, digitally graded superlattice hetero-interfaces and superlattice electron barriers [47] for dark current suppression has been developed. Figure 4 shows the typical

characteristics of the photodetectors of 500 μm diameter, its 50% cut-off wavelength at RT is about 2.6 μm. For the development of FPAs, the material and processing related parameters affect the uniformity of the device also have been investigated [48,49], as well as related material and device features [50-52].
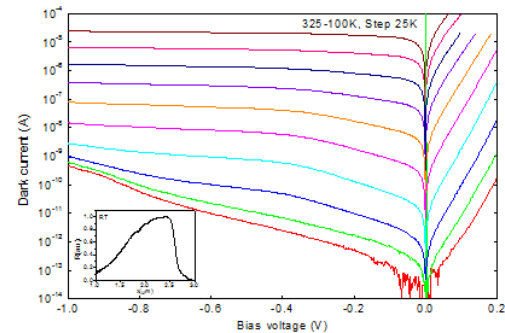

Figure 4: Dark current characteristics of the high indium content InGaAs photodetector at different temperatures (φ = 500 μm), the inset shows its response spectrum at room temperature (50% cutoff at ∼ 2.6 μm).
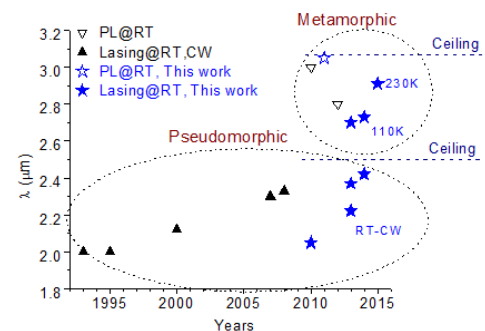

Figure 5: R&D trends of the InP-based antimony-free lasers in 2-3 μm band, the ceiling heights of the pseudomorphic and metamorphic schemes are supposed to be at about 2.5 μm and 3.0 μm respectively.

Applications

The R&D of the lasers and photodetectors are target on actual applications. As for the lasers below 2.5 μm, RT-CW operation has been reached with moderate power. Based on those devices battery-driven miniaturized laser modules have been developed, which have been used for the characterization of the photodetector materials and devices favorably, as well as some other utilities. As for the photodetectors, by using of gas source grown epitaxial wafers with optimized structure, FPA chips, devices and modules have been developed by Shanghai Institute of Technical Physics target on space applications, such as meteorology and ocean, resource and circumstance, lunar exploration, manned spaceflight, etc.

Conclusion

In conclusion, Figure 5 shows the R&D trends of the InP-based antimony-free lasers in 2-3 μm band. It could be seen that, 2.43 μm RT-CW operation of the laser have been reached using pseudomorphic scheme, whereas 2.9 μm operation of the laser only have been reached at thermoelectric cooling temperature using metamorphic scheme. The ceiling heights of the pseudomorphic and metamorphic schemes are supposed to be at about 2.5 μm and 3.0 μm respectively.

The cutoff wavelength of the high indium content InGaAs photodetector have been extended to 2.9 μm [46], but for longer wavelength the performance degradation of the device is fast than expected. As an overall consideration the RT cutoff wavelength of 2.5-2.6 μm are favorable for applications.

Acknowledgement

References

1. Li AZ, Zhao Y, Zheng YL, Chen GT, Ru GP, et al. (1997) MBE growth and characterization of high quality GaInAsSb/AlGaAsSb strained multiple quantum well structures. J Crystal Growth 175: 873-876.

2. Zhang YG, Li AZ, Zheng YL, Lin C, Jian GZ (2001) MBE grown 2.0 μm InGaAsSb/AlGaAsSb MQW ridge waveguide laser diodes. J Crystal Growth, 227/228: 582-585.

3. Zhang YG, Zheng YL, Li AZ, Lin C, Liu S (2006) Continuous wave and tunability of MBE grown 2.1 μm InGaAsSb/AlGaAsSb MQW lasers. Chin Phys Lett 23: 2262-2265.

4. Zhang YG, Zhang XJ, Zhu XR, Li AZ, Liu S (2007) Tunable diode laser absorption spectroscopy detection of N2O at 2.1μm using antimonide laser and InGaAs photodiode. Chin Phys Lett 24: 2301-2303.

5. Zhang YG, Tian ZB, Zhang XJ, Gu Y, Li AZ, et al. (2007) An innovative gas sensor with on-chip reference using monolithic twin lasers. Chin Phys Lett 24: 2839-2841.

6. Zhang YG, Gu Y, Zhang XJ, Li AZ, Tian ZB (2008) Gas sensor using a robust approach under time multiplexing scheme with a twin laser chip for absorption and reference. Chin Phys Lett 25: 3246-3249.

7. Yang RQ (1995) Infrared laser based on intersubband transitions in quantum wells. Superlattices & Microstructure 17: 77-83.

8. Yang RQ, Hill CJ, Yang BH (2005) High-temperature and low-threshold midinfrared interband cascade lasers. Appl Phys Lett 87: 151109.

9. Devenson J, Barate D, Cathabard O, Teissier R, Baranov AN (2006) Very short wavelength (λ = 3.1 – 3.3 μm) quantum cascade lasers. Appl Phys Lett 89: 191115.

10. Cathabard O, Teissier R, Devenson J, Moreno JC, Baranov AN (2010) Quantum cascade lasers emitting near 2.6 μm. Appl Phys Lett 96: 141110.

11. Baranov AN, Cuminal Y, Boissier G, Alibert C, Joullié A (1996) Low-threshold laser diodes based on type-II GaInAsSb/GaSb quantum-wells operating at 2.36 μm at room temperature. Electron Lett 32: 2279-2280.

12. Rossner K, Hummer M, Lehnhardt T, Muller M, Forchel A, et al. (2006) Continuous-wave operation of GaInAsSb/GaSb type-II ridge waveguide lasers emitting at 2.8 μm. IEEE Photon Technol Lett 8: 1424-1426.

13. Shterengas L, Liang R, Kipshidze G, Hosoda T, Suchalkin S, et al. (2013) Type-I quantum well cascade diode lasers emitting near 3 μm. Appl Phys Lett 103: 121108.

14. Laffaille P, Moreno JC, Teissier R, Bahriz M, Baranov AN (2012) High temperature operation of short wavelength InAs-based quantum cascade lasers. AIP Advances 2: 022119.

15. Li L, Jiang YC, Ye H, Yang RQ, Mishima TD, et al. (2015) Low-threshold InAs-based interband cascade lasers operating at high temperatures. Appl Phys Lett 106: 251102.

16. Forouhar S, Ksendzov A, Larsson A, Temkin H (1992) InGaAs/InGaAsP/InP strained layer quantum well lasers at approximately 2m μm. Electron Lett 28: 1431-1342.

17. Bandyopadhyay N, Bai Y, Tsao S, Nida S, Slivken S, et al. (2012) Room temperature continuous wave operation of λ ~ 3-3.2 μm quantum cascade lasers. Appl Phys Lett 101: 241110.

18. Yang QK, Manz C, Bronner W, Köhler K, Wagner J (2006) Room-temperature short-wavelength (λ ~ 3.7 - 3.9 μm) GaInAs/AlAsSb quantum-cascade lasers. Appl Phys Lett 88: 121127.

19. Revina DG, Cockburn JW, Steer MJ, Airey RJ, Hopkinson M, et al. (2007) InGaAs/AlAsSb/InP quantum cascade lasers operating at wavelengths close to 3 μm. Appl Phys Lett 90: 021108.

20. Sprengel S, Andrejew A, Vizbaras K, Gruendl T, Geiger K, et al. (2012) Type-II InP-based lasers emitting at 2.55 μm. Appl Phys Lett 100: 041109.

21. Chang CH, Li ZL, Pan CH, Lu HT, Lee CP, et al. (2014) Room-temperature mid-infrared "M"-type GaAsSb/InGaAs quantum well lasers on InP substrate. J Appl Phys 115: 063104.

22. Gu Y, Zhang YG (2015) InP-based antimony-free MQW lasers in 2-3 μm band. In: Optoelectronics-materials and devices. Chapter 4, InTech Croatia.

23. Zhang YG, Zhou P, Chen HY, Pan HZ (1990) LPE growth of InAsPSb on InAs: melt composition, lattice mismatch and surface morphology. Chin J Rare Metals 9: 46-51.

24. Zhang YG, Zhou P, San HK, Pan HZ (1992) InAsPSb/InAs mid-infrared photodetectors. Chin J Semiconductors 13: 623-628.

25. Li AZ, Zhong JQ, Zheng YL, Wang JX, Ru GP, et al. (1995) MBE growth, characterization and performance of InGaAsSb PIN detectors operating at 2.0 to 2.6 μm. J Crystal Growth 150: 1375-1378.

26. Zhang YG, Gu Y (2011) Gas source MBE grown wavelength extending InGaAs photodetectors. In: Advances in photodiodes. Chapter 19, InTech, Croatia.

27. Gu Y, Zhang YG, Liu S (2007) Strain compensated AlInGaAs/InGaAs/InAs triangular quantum wells for lasing wavelength beyond 2 μm. Chin Phys Lett 24: 3237-3240.

28. Gu Y, Zhang YG (2008) Properties of strain compensated symmetrical triangular quantum wells composed of InGaAs/InAs chirped superlattice grown using gas source molecular beam epitaxy. Chin Phys Lett 25: 726-729.

29. Gu Y, Zhang YG, Wang K, Li AZ, Li YY (2009) Optimization of AlInGaAs/InGaAs/InAs strain compensated triangular quantum wells grown by gas source molecular beam epitaxy for laser applications in 2.1-2.4 μm range. J Crystal Growth 311: 1935-1938.

30. Gu Y, Wang K, Li YY, Li C, Zhang YG (2010) InP-based InGaAs/InAlGaAs digital alloy quantum well laser structure at 2 μm. Chin Phys B 19: 077304.

31. Cao YY, Gu Y, Zhang YG, Li YY, Fang X, et al. (2014) InAs/InGaAs digital alloy strain-compensated quantum well lasers. J Infrared Millim Waves 33: 213-217.

32. Gu Y, Zhang YG, Chen XY, Cao YY, Zhou L, et al. (2015) Effects of well widths and well numbers on InP-based triangular quantum well lasers beyond 2.4 μm. J Crystal Growth 425: 376-380.

33. Cao YY, Zhang YG, Gu Y, Chen XY, Zhou L, et al. (2014) Improved performance of 2.2 μm InAs/InGaAs QW lasers on InP by using triangular wells. IEEE Photon Technol Lett 26: 571-574.

34. Gu Y, Zhang YG, Cao YY, Zhou L, Chen XY, et al. (2014) 2.4-μm InP-based antimony-free triangular quantum well lasers in continuous-wave operation above room temperature. Appl Phys Express 7: 032701.

35. Gu Y, Zhang YG, Wang K, Fang X, Li C, et al. (2011) InP-based InAs/InGaAs quantum wells with type-I emission beyond 3 μm. Appl Phys Lett 99: 081914.

36. Gu Y, Zhang YG, Chen XY, Cao YY, Fang X, et al. (2013) InAs/In0.83Al0.17As quantum wells on GaAs substrate with type-I emission at 2.9 µm. Appl Phys Lett 102: 121110.

37. Gu Y, Chen XY, Zhang YG, Cao YY, Fang X, et al. (2013) Type-I mid-infrared InAs/InGaAs quantum well lasers on InP-based metamorphic InAlAs buffers. J Phys D Appl Phys 46: 505103.

38. Cao YY, Zhang YG, Gu Y, Chen XY, Zhou L, et al. (2013) 2.7 µm InAs quantum well lasers on InP-based InAlAs metamorphic buffer layers. Appl Phys Lett 102: 201111.

39. Gu Y, Zhang YG, Ma YJ, Zhou L, Chen XY, et al. (2015) InP-based type-I quantum well lasers up to 2.9 µm at 230 K in pulsed mode on a metamorphic buffer. Appl Phys Lett 106: 121102.

40. Zhang YG, Hao GQ, Gu Y, Zhu C, Li AZ, et al. (2005) 1.9 µm InGaAs PIN photodetectors grown by gas source MBE. Chin Phys Lett 22: 250-253.

41. Zhang YG, Gu Y, Zhu C, Hao GQ, Li AZ, et al. (2006) Gas source MBE grown wavelength extended 2.2 and 2.5 µm InGaAs PIN photodetectors. Infrared Physics & Technology. 47: 257-262.

42. Zhang YG, Gu Y, Tian ZB, Li AZ, Zhu XR, et al. (2008) Wavelength extended 2.4 µm heterojunction InGaAs photodiodes with InAlAs cap and linearly graded buffer layers suitable for both front and back illuminations. Infrared Physics & Technology 51: 316-321.

43. Zhang YG, Gu Y, Wang K, Li AZ, Li C (2008) Properties of gas source molecular beam epitaxy grown wavelength extended InGaAs photodetector structures on linear graded InAlAs buffer. Semicon Sci Technol 23: 125029.

44. Zhang YG, Gu Y, Tian ZB, Li AZ, Zhu XR, et al. (2009) Wavelength extended InGaAs/InAlAs/InP photodetectors using n-on-p configuration optimized for back illumination. Infrared Physics & Technology 52: 52-56.

45. Zhang YG, Gu Y, Tian ZB, Wang K, Li AZ, et al. (2009) Performance of gas source MBE grown wavelength extended InGaAs photodetectors with different buffer structures. J Crystal Growth 311: 1881-1884.

46. Li C, Zhang YG, Wang K, Gu Y, Li HSBY, et al. (2010) Distinction investigation of InGaAs photodetectors cutoff at 2.9 µm. Infrared Physics & Technology 53: 173-176.

47. Gu Y, Zhou L, Zhang YG, Chen XY, Ma YJ, et al. (2015) Dark current suppression in metamorphic In0.83Ga0.17As photodetectors with In0.66Ga0.34As/InAs superlattice electron barrier. Appl Phys Express 8: 022202.

48. Gu Y, Zhang YG, Li C, Wang K, Li HSBY, et al. (2011) Analysis and evaluation of uniformity of SWIR InGaAs FPA-Part I: material issues. Infrared Physics & Technology 54: 497-502.

49. Li C, Zhang YG, Gu Y, Wang K, Li HSBY, et al. (2013) Analysis and evaluation of uniformity of SWIR InGaAs FPA-Part II: processing issues and overall effects. Infrared Physics & Technology 58: 69-73.

50. Zhou L, Zhang YG, Gu Y, Chen XY, Cao YY, et al. (2013) Absorption coefficients of In0.8Ga0.2As at room temperature and 77 K. J Alloys and Compounds 576: 336-340.

51. Zhou L, Zhang YG, Gu Y, Ma YJ, Chen XY, et al. (2015) Effects of material parameters on the temperature dependent spectral response of In0.83Ga0.17As photodetectors. J Alloys and Compounds 619: 52-57.

52. Ma YJ, Gu Y, Zhang YG, Chen XY, Xi SP, et al. (2015) Carrier scattering and relaxation dynamics in n-type In0:83Ga0:17As as a function of temperature and doping density. Journal of Materials Chemistry C 3: 2872-2880.