بیست و سومین کنفرانس اپتیک و فوتونیک و نهمین کنفرانس مهندسی و فناوری فوتونیک ایران
دانشگاه تربیت مدرس
۱۲-۱۴ بهمن ۱۳۹۵
23rd Iranian Conference on Optics and Photonics and 9th Conference on Photonics Engineering and Technology
Tarbiat Modares University, Tehran, Iran
January 31- February 2, 2017

طراحی آشکارساز فرابنفش بر پایه لیزرهای چاه پتانسیل پمپینگ نوری

صبا خسروی[۱]، علی رستمی[۱و۲]، محبوبه دولتیاری [۲]و قاسم رستمی[۲]

[۱] آزمایشگاه تحقیقاتی فوتونیک و نانوکریستال دانشکده مهندسی برق و کامپیوتر دانشگاه تبریز، تبریز-ایران ۵۱۶۶۶۱۴۷۶۱

[۲] شرکت آرمان جستجوگران انرژی نور، تبریز-ایران

چکیده – هدف اصلی این تحقیق طراحی یک آشکارساز فرابنفش بر پایه گذارهای داخل باندی در چاههای پتانسیل ساخته شده از ترکیبات عناصر گروه سوم جدول تناوبی و نیتروژن میباشد. به دلیل فراوانی آشکارسازهای نور مرئی، لیزرهای با پمپینگ نوری با قابلیت تبدیل تابش برخوردی فرابنفش به نورمریی پیشنهاد شده است. طول موج تابشی حدود ۳۵۲*nm* در ناحیه طول موجی فرابنفش به طول موج مریی *nm* ۵۵۹ با استفاده از گذارهای داخل باندی در ساختارهای چاه پتانسیل ترکیبات عناصر گروه سوم جدول تناوبی و نیتروژن ، تبدیل میشود. به منظور محاسبه پارامترهای آشکارساز، توابع موج و ترازهای انرژی با حل خودسازگار معادله شرودینگر-پواسون در دمای ۳۰۰*K*° بدست آمده-اند. بهره نوری ساختار در دمای ۳۰۰*K*° (*1/cm*)۱۰/۲۸ است.

کلید واژه- آشکار ساز فرابنفش، چاه پتانسیل، لیزر پمپینگ نوری، بهره نوری

Design of Ultraviolet photodetector based on Quantum Well Optically Pumped Lasers

Saba Khosravi[1], Ali Rostami[1,2], Mahboubeh Dolatyari[2], and Ghassem Rostami[2]

[1] Photonics and Nanocrystal Research Lab. (PNRL), Faculty of Electrical and Computer Engineering, University of Tabriz, Tabriz 5166614761, Iran
[2] SP- EPT Labs., ASEPE Company, Industrial Park of Advanced Technologies, Tabriz, Iran

Abstract- The main goal of this research is design of an ultraviolet photodetector based on intersubband transitions in III-Nitride multiple quantum well. Due to the abundance of visible light detectors, optically pumped lasers with ability of converting incident ultraviolet radiation to visible light are proposed. In this way, incident wavelength of about 352nm at ultraviolet wavelength band is converted to wavelength of 559nm at visible range using intersubband transitions in III-Nitride multiple quantum well structures.To calculate parameters of the structure, wave functions and energy levels are obtained by solving 1-D Schrodinger–Poisson equation self consistently at 300°K. Responsivity and optical gain for the designed structure are 4.623(mA/w) and 10.28 (1/cm) at 300°K respectively.

Keywords: Ultravilet photodetector, Quantum Well, Optically Pumped Laser, Optical Gain

23rd Conference on Optics and Photonics and 9th Conference on Photonics Engineering and Technology
January 31-February 2 2017

Design of Ultraviolet Photodetector based on Quantum Well Optically Pumped Lasers

Saba Khosravi[1], Ali Rostami[1,2]
[1] PNR, Lab, Faculty of Electrical and Computer Engineering, University of Tabriz, Tabriz, Iran
skhosravi@tabrizu.ac.ir

Mahboubeh Dolatyari[2],and Ghassem Rostami[2]
[2] SP- EPT Labs., ASEPE Company, Industrial Park of Advanced Technologies, Tabriz, Iran
rostami@tabrizu.ac.ir

1 Introduction

Ultraviolet (UV) detectors due to their applications in monitoring of UV radiation, flame detection, missile warning systems, are interested for researchers [1]. UV photodetectors based on large band gap materials such as SiC, GaN, AlGaN, ZnO and $Mg_xZn_{1-x}O$ for detecting photons with high energy are designed [2-4]. III-Nitride materials with wide band gap are commercialized in full-color LCD displays, traffic light, CD/DVD write systems [1]. Also, GaN alloys are confident material in power electronic transistor and thyristors. Photodetectors made of $Al_xGa_{1-x}N$ are able to detect wavelength range of 200-360nnm by adjusting the Al mole fraction. For this reason structures based on $Al_xGa_{1-x}N$ as quantum wells are introduced [4].
In the other hand, population inversion of lasing levels is realized by electrical and optical pumping. Single and dual color lasers in terahertz radiation with electrical pumping are designed based on intersubband transitions in multi quantum wells (MQW) [5, 6]. In these structures, the upper lasing level is populated by an external radiation. Optically pump lasers are important due to using low cost pumping lasers such as CO_2 [6].
Due to the importance of UV photodetectors and abundance of visible photodetectors, in this paper, a UV photodetector with ability of converting the incident high energy photons with energy of 3.52ev (352.5nm) in UV band to low energy photons with energy of 2.21ev (559.5nm) in visible range is designed. Photons with high energy are converted to photons with low energy levels by emitting optical phonon with energy of 90mev by intersubband transitions in III-Nitride MQWs quantum cascade detectors. In this way the proposed photodetector acts as a visible light laser with optical pumping. To calculate the detector parameters and optical gain, wave functions and energy levels are obtained by solving 1-D Schrödinger and Poisson equations self consistently, at 300°K. Responsivity and optical gain of the designed structure are obtained as 4.623(mA/w) and 10.28 (1/cm) at 300°K respectively.

2 Theoretical Background and Simulation Results

A 3-D view of the proposed photodetector with ability of converting UV to visible radiation is shown in Figure 1. The structure consists of 20 periods III-Nitride MQWs with the wells and barriers thickness listed in Table 1.
The concentration of n-doped InN QWs in each period is 5×10^{11} cm^{-2}. Conduction band edge, energy levels and wave functions for the designed structure are shown in Figure 2. Wave functions and confined energy levels are obtained at 300°K, by solving 1-D Schrödinger and Poisson equations self consistently for III-Nitrides MQWs structures [7]. Incoming UV radiation with wavelength of 352.2 excites electrons in n-doped InN well from the ground state (level 1) to level 16 based on intersubband transitions. Photoexcited electrons reach level 3 by emitting the optical phonons close to *GaN* LO-phonon energy (90meV). Visible wavelength of 559.5nm is generated by transition of carriers from level 3 to level 2.

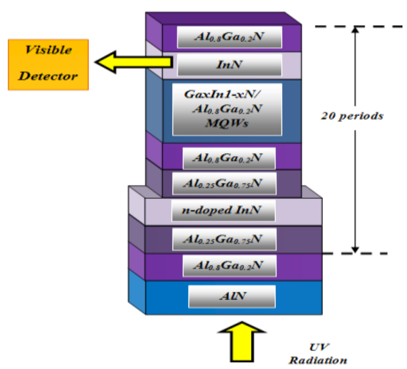

Figure 1. A 3-D view of the UV photodetector structure with ability of converting UV to visible radiation.

Table 1. Thickness of the wells and barriers for MQWs.

Wells	**Thickness (Å)**	**Barriers**	**Thickness (Å)**
$Al_{0.25}Ga_{0.75}N$	**10**	**$Al_{0.8}Ga_{0.2}N$**	**50**
InN	**15.4**	**$Al_{0.8}Ga_{0.2}N$**	**10**
$Al_{0.25}Ga_{0.75}N$	**10**	**$Al_{0.8}Ga_{0.2}N$**	**15**
$Al_{0.217}Ga_{0.783}N$	**10**	**$Al_{0.8}Ga_{0.2}N$**	**15**
$Al_{0.215}Ga_{0.785}N$	**12**	**$Al_{0.8}Ga_{0.2}N$**	**15**
$Al_{0.242}Ga_{0.758}N$	**14**	**$Al_{0.8}Ga_{0.2}N$**	**15**
$Al_{0.259}Ga_{0.741}N$	**17**	**$Al_{0.8}Ga_{0.2}N$**	**15**
$Al_{0.243}Ga_{0.757}N$	**19**	**$Al_{0.8}Ga_{0.2}N$**	**15**
$Al_{0.227}Ga_{0.773}N$	**21**	**$Al_{0.8}Ga_{0.2}N$**	**15**
$In_{0.08}Ga_{0.92}N$	**16**	**$Al_{0.8}Ga_{0.2}N$**	**15**
$In_{0.078}Ga_{0.922}N$	**18**	**$Al_{0.8}Ga_{0.2}N$**	**15**
$In_{0.097}Ga_{0.903}N$	**21**	**$Al_{0.8}Ga_{0.2}N$**	**15**
$In_{0.085}Ga_{0.915}N$	**23**	**$Al_{0.8}Ga_{0.2}N$**	**15**
$In_{0.06}Ga_{0.94}N$	**24**	**$Al_{0.8}Ga_{0.2}N$**	**15**
$In_{0.057}Ga_{0.943}N$	**27**	**$Al_{0.8}Ga_{0.2}N$**	**10**
$In_{0.055}Ga_{0.945}N$	**30**	**$Al_{0.8}Ga_{0.2}N$**	**10**
InN	**15.3**	**$Al_{0.8}Ga_{0.2}N$**	**10**
$Al_{0.25}Ga_{0.75}N$	**10**	**$Al_{0.8}Ga_{0.2}N$**	**10**
InN	**14.8**	**$Al_{0.8}Ga_{0.2}N$**	**15**
$Al_{0.25}Ga_{0.75}N$	**10**		

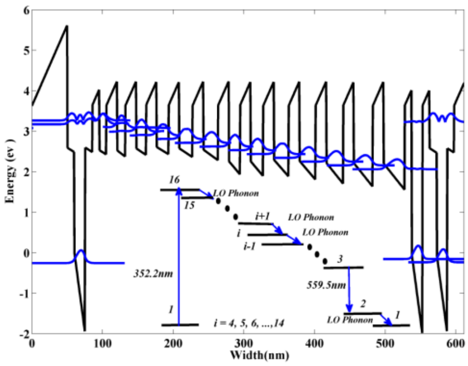

Figure 2. Conduction band edge, energy levels and wave functions for the designed structure.

The absorption coefficient is obtained as "Equation (1)": [7].

$$\alpha(\omega)=\frac{\omega\mu c e^{2}}{n}\left|M_{fi}\right|^{2}\frac{m^{*}k_{B}T}{L eff\pi\hbar^{2}}\ln\left\{\frac{1+\exp[(E_{F}-E_{i})/k_{B}T}{1+\exp[(E_{F}-E_{f})/k_{B}T}\right\}\times \frac{\hbar/\tau_{in}}{(E_{f}-E_{i}-\hbar\omega)^{2}+(\hbar/\tau_{in})^{2}} \quad (1)$$

Where, E_i and E_f, are the quantized energy levels for the initial and final states, respectively. M_{fi} , μ , c , L_{eff} , n and τ_{in} are dipole matrix element between initial and final states, the permeability, the speed of light in free space, the effective spatial extent of electrons in subbands, the refractive index of InN and the intersubband relaxation time respectively. The absorption coefficient at 300˚K is shown in Figure 3.

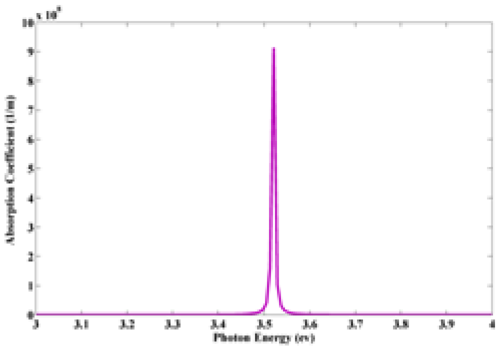

Figure 3. Absorption coefficient as a function of incident photon energy.

The peak of absorption coefficient is corresponding to 3.52ev (352.2μm). The responsivity R is obtained as "Equation 2" [7]:

$$R=\eta\frac{\lambda q P_{e}}{N_{QW}hcP_{c}} \quad (2)$$

Where, λ, q, h, η, P_e, P_c, N_{QW} are the incident wavelength, the elementary charge, Planck's constant, the quantum efficiency, the escape probability of an excited electron in active QW, capture probability into the active QW's ground state for an electron travelling down the QCD's cascade and the number of active QW periods of the QCD. The escape probability of an excited electron in active QW and capture probability into the active QW's ground state are considered as 0.5 and 1 respectively. Absorption efficiency is determined by "Equation 3" [7]:

$$\eta=1-e^{-\alpha(\omega)d} \quad (3)$$

Where, α and *d* are the absorption coefficient and thickness of active well in each period respectively. The responsivity for the photodetector structure at 300˚K is indicated in Figure 4.

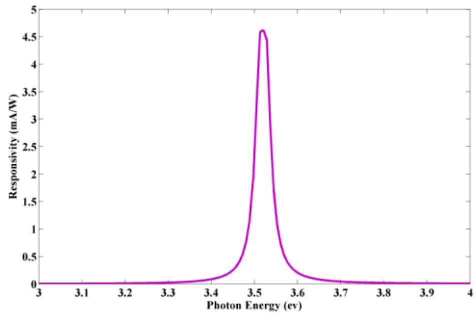

Figure 4. The responsivity for the photodetector structure at 300˚K versus photon energy.

The scattering rates between energy levels are determined by non-radiative processes [5]. Electron-LO phonon interaction is considered as the more dominant mechanism than the electron-electron interaction for low level populations [6]. In the other hand the other non-radiative mechanisms such as interface roughness and impurity scattering effects is neglected in our calculations for simplicity.
To calculate the optical gain, the population dynamics of the proposed systems is obtained by solving rate equations in steady state condition [5].
The optical gain is determined by “Equation 4” [5]:

$$\gamma = \frac{2e^2 |\langle 3|z|2\rangle|^2}{n\varepsilon_0(\hbar\Gamma_{23})} \frac{2\pi}{\lambda_0}(N_3 - N_2)$$
(4)

Where, <2|z|3>, λ_0 and $\hbar\Gamma_{23}$ are matrix element between |2> and |3> states, free space lasing wavelength and full width at half maximum of radiation line. Optical gain and electron densities of lasing states for pump intensity of $2.48 kW/cm^2$ at 300°K are listed in Table 4.

Table 4. Optical gain and electron densities of lasing states for pump intensity of $2.48 kW/cm^2$ at 300°K

Temperature (°K)	γ (1/cm)	N_2 (1/cm^3)	N_3(1/cm^3)
300	10.28	9.55×10^{16}	6.22×10^{18}

3 Conclusions

In this paper, UV photodetector based on intersubband transitions III-Nitride MQWs was designed. The incident photon with high energy of 3.52ev (352.5nm) at UV band was converted to photons with low energy of 2.21ev (559.5nm) at visible range.

Acknowledgements

This work is supported by Photonics and Nanocrystal research Lab. (PNRL), Faculty of Electrical and Computer Engineering of Tabriz University.

References

[1] M. Razeghi and A. Rogalski,“Semiconductor ultraviolet detectors” Journal of applied Physics, Vol. 79, No. 7433, (42 pages), 1996.
[2] T.H. Moon, M.C. Jeong, W. Lee and J.M. Myoung, “The fabrication and characterization of ZnO UV detector” Applied Surface Science, vol. 240, pp. 280-285, 2005.
[3] X. Chen, H. Zhu, J. Cai and Z. Wu,”High-performance 4H-SiC-based ultraviolet *p-i-n* photodetector” Journal of Applied Physics, vol, 102, No. 024505 (4 pages), 2007 .
[4] S. Aslam, L. Miko, C. Stahle, D. Franz, D. Pugel, B. Guan, J.P. Zhang and R. Gaska,”Dual-band deep ultraviolet AlGaN photodetectors”, Electronics Letters, Vol. 43 No. 24, pp. 1-2, 2007.
[5] Gang Sun and Jacob B. Khurgin,”Optically Pumped Four-Level Infrared Laser Based on Intersubband Transitions in Multiple Quantum Wells: Feasibility Study”, IEEE Journal of Quantum Electronics, vol. 29. No. 4, pp.1104-1111, 1993.
[6] A. Rostami, H. Baghban, H. Rasooli Saghai," An ultra-high level second-order nonlinear optical susceptibility in strained asymmetric GaN–AlGaN–AlN quantum wells: Towards all-optical devices and systems," Microelectronics Journal, no. 38, pp. 900–904, 2007.
[7] A. Rostami, R. Oliaee Rezaee, H. Rasooli Saghai, R. Yadipour, and H. Baghban, “A dual-color IR quantum cascade photodetector with two output electrical signals”,IEEE Transaction on Electron Devices, vol. 58, pp. 165-172, 2010.