Low voltage operation of electro-absorption modulator promising for high-definition 3D imaging application using a three step asymmetric coupled quantum well structure

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Abstract. In this paper, we propose a transmission type electro-absorption modulator (EAM) operating at 850 nm having low operating voltage and high absorption change with low insertion loss using a novel three step asymmetric coupled quantum well (3 ACQW) structure which can be used as an optical image shutter for high-definition (HD) three dimensional (3D) imaging. Theoretical calculations show that the exciton red shift of 3 ACQW structure is more than two times larger than that of rectangular quantum well (RQW) structure while maintaining high absorption change. The EAM having coupled cavities with 3 ACQW structure shows a wide spectral bandwidth and high amplitude modulation at a bias voltage of only -8V, which is 41% lower in operating voltage than that of RQW, making the proposed EAM highly attractive as an optical image shutter for HD 3D imaging applications.

1. Introduction

Optical image shutter is an important component for realizing high-definition (HD) three dimensional (3D) imaging systems. Low voltage operation, high speed operation and wide bandwidth are the key requirements of such an optical image shutter. Over the past years, several optical image shutters such as Kerr cells [1], liquid crystal or mechanical shutter [2] and micro channel plate (MCP) [3] were proposed. They however have several drawbacks. Of them, Kerr cells suffer from extremely high operating voltage while the modulation speed of liquid crystal or mechanical shutter is limited to few kHz. MCP is not only expensive and bulky but also requires high voltage for its operation. These shutters are therefore not suitable for reliable high-definition (HD) 3D imaging system. Recently, surface normal electro-absorption modulator (EAM) which can function as optical image shutter operating at wavelength near 850 nm based on quantum-confined Stark effect (QCSE) was developed [4]. The reliable operation of EAM with high amplitude modulation over wide wavelength range was reported. However, the reported EAM still suffer from high operating voltage at high modulation speeds, which increases power consumption and the generated heat in the system which significantly degrades the modulation performance. In the past years, several band-gap engineering techniques has been extensively studied in GaAs/AlGaAs quantum well (QW) system such as stepped QW [5], symmetric [6], asymmetric [7] and partially doped coupled QW [8] to reduce the operating voltage. In case of symmetric and asymmetric coupled QW, these structures have a large residual absorption

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limiting high amplitude modulation. Doped coupled QW operate only at low temperatures and due to the high doping concentration in QW region, significant broadening of absorption spectra occurs leading to low contrast ratio which limits their usage, whereas stepped QW did not show any improvement in modulation performance.

In this paper, we present the design and simulation of transmission type EAM structure having high amplitude modulation with wide spectral bandwidth operating at low bias voltage. These improved features are achieved by using a novel three step GaAs/AlGaAs asymmetric coupled quantum well (3 ACQW) structure for the EAM. Theoretical calculations show that the exciton red shift of 3 ACQW structure is more than two times larger than that of rectangular quantum well (RQW) structure while maintaining high absorption variation. The EAM having coupled cavities with 3 ACQW structure show a wide spectral bandwidth and large amplitude modulation at a bias voltage of only -8V, which is 41% lower than that of RQW. These simulation results reveal that EAM with 3 ACQW structure are promising as optical image shutter for HD 3D imaging systems.

2. Design of 3 ACQW for low voltage operation and large absorption modulation

Low voltage operation can be achieved in coupled GaAs/$Al_xGa_{1-x}As$ QW by optimizing the coupling barrier thickness and height [9, 10, 11]. For an applied electric field, the electron and hole wave functions of coupled QW are shifted rapidly compared to that of RQW, resulting in lower operating voltage. However, a rapid shift of wave functions to opposite directions greatly reduces the overlap of electron and hole wave functions leading to a weak oscillator strength and therefore to a lower electro-absorption. Consequently, in spite of having low operating voltage, the coupled QW structure suffers from low absorption modulation. The key idea of our purposed structure lie in increasing the overlap of electron and hole wave functions while simultaneously reducing the operating voltage, which is attributed to asymmetric, thin and low height coupling barrier. All absorption spectrums were calculated using commercial APSYS program [12]. For the calculation, the Schrodinger equation was numerically solved with appropriate boundary conditions in order to obtain the eigen values (particle energies) and energy states (wave functions).

Figure 1 (a) and (b) respectively shows the calculated electron and hole wave functions of the RQW and 3 ACQW structures at different applied electric fields. The RQW structure consists of 8 nm thick GaAs well and a 4 nm thick $Al_{0.3}Ga_{0.7}As$ barrier, and the 3 ACQW structure consists of 3 nm thick, 6.6 nm thick and 2 nm thick GaAs wells separated by two 1 nm thick $Al_{0.2}Ga_{0.8}As$ barrier. The barrier is sufficiently thin so that the particle wave functions of adjacent wells can couple to each other. In case of RQW, the wave functions are not seriously distorted with applied fields. On the other hand, in the 3 ACQW with properly chosen position of the barrier, the wave functions are seriously distorted, leading to much larger dependence of electro absorption on applied field. As a result, the red shift of the 3 ACQW structure is almost two times larger than that of RQW structure. In addition, the absorption coefficient of 3 ACQW structure is larger than that of RQW due to large overlap of electron and hole wave functions.

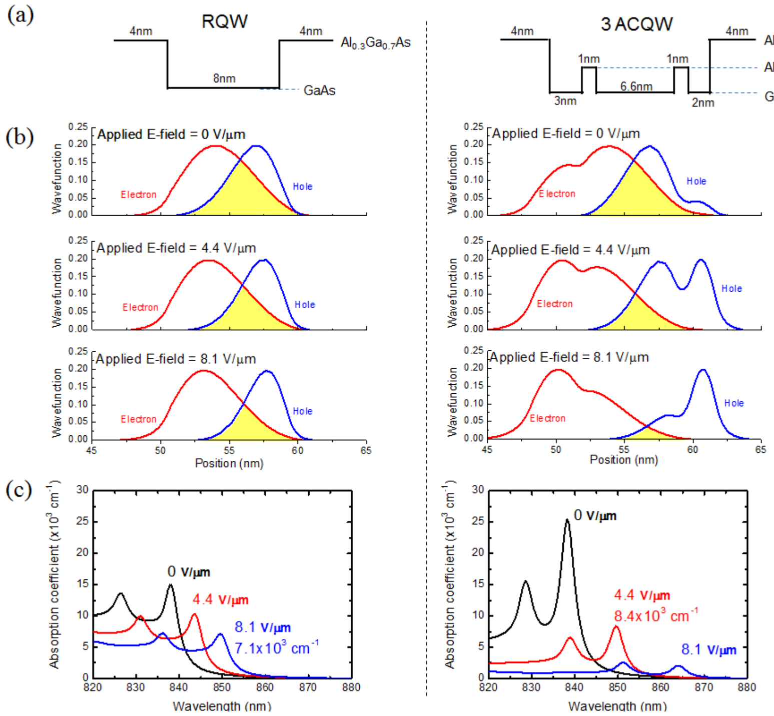

Figure 1 (a) Quantum well structure (b) electron and hole wave functions, and (c) absorption coefficient of RQW(left) and 3 ACQW(right) structures at an applied electric fields of 0, 4.4 and 8.1 V/μm. The yellow region indicates the wave function overlap..

3. Design of low voltage operation electro-absorption modulator

To confirm the feasibility of EAM with 3 ACQW for low voltage operation and high amplitude modulation, we have designed and fabricated the EAM with RQW and with 3 ACQW using a combination of coupled Fabry-Perot cavity with micro-cavity (CCMC) [13].

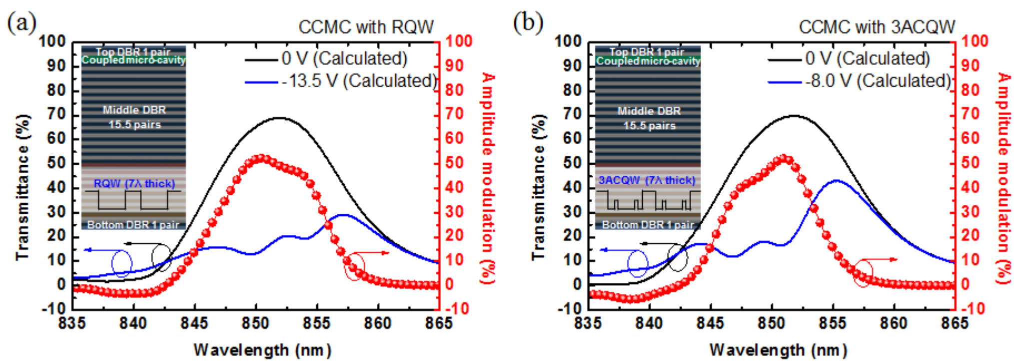

Figure 2 Transmittance and amplitude modulation of CCMC with (a) RQW structure, (b) 3 ACQW structure. The inset of (a) and (b) show the schematic of CCMC with RQW structure and 3 ACQW structure, respectively.

The structures shown in the insets of Figure 2 (a) and (b) have a 7-λ thick cavity sandwiched between one pair of bottom DBR and 15.5 pairs of middle DBR for both structures. On the top of middle DBR is the micro-cavity followed by one pair of top DBR. In the CCMC with RQW structure, the active layer consists of 60 and 78 pairs of 8 nm thick and 8.5 nm thick GaAs RQW, respectively. For CCMC with 3 ACQW structure, the active layer consists of 45 and 50 pairs of 6.6 nm thick and 6.0 nm thick GaAs QW, respectively which is placed in the middle of 3 ACQW structure. Figure 2 shows the calculated transmittance spectra and amplitude modulation for CCMC having RQW and 3

ACQW structures. It can be seen that for CCMC with 3 ACQW structure, the operating voltage is reduced by about 41% compared to CCMC with RQW structure, while maintaining a broad spectral bandwidth with high amplitude modulation over 50%.

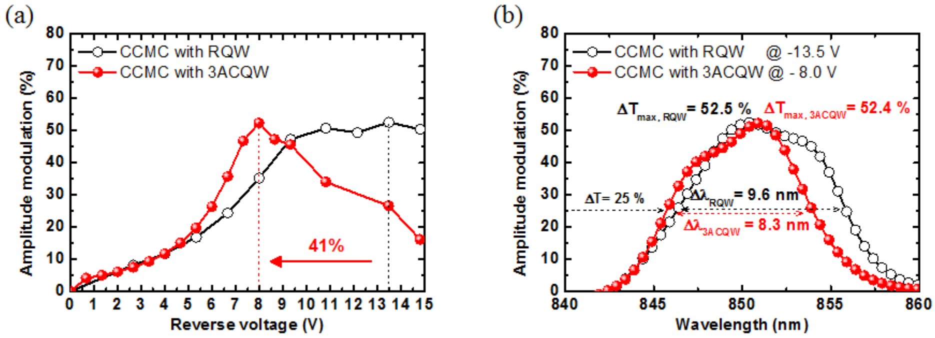

Figure 3 The amplitude modulation of CCMC with RQW and 3 ACQW (a) at operating wavelength for different applied bias voltages and (b) at operating voltage.

Figure 3 shows the amplitude modulation of CCMC with RQW and 3 ACQW as a function of applied bias and wavelength. From Fig 3(a), it can be seen that the amplitude modulation increases as the applied bias voltages increases and show a maximum when exciton peak wavelength coincides with the operating wavelength. The maximum amplitude modulation of CCMC with 3 ACQW structure occurs at a bias voltage of -8 V which is 41% lower compared to that of CCMC with RQW structure. For CCMC with 3 ACQW at operating voltage (-8 V), the amplitude modulation and spectral bandwidth (for △T = 25%) are 52.4% and 8.3 nm, respectively, as shown Figure 3 (b). Even though CCMC with RQW shows a higher spectral bandwidth (9.6 nm) compared to CCMC with 3 ACQW, the former requires a much larger bias of -13.5V. It is noteworthy that the operating voltage of CCMC with 3 ACQW was significantly reduced by 41% while simultaneously maintaining high amplitude modulation (>50%) and wide spectral bandwidth (>8 nm), demonstrating their capability to be used as optical shutter for high-definition imaging applications.

4. Conclusion

We have proposed a novel 3 ACQW structure for EAM to simultaneously achieve low voltage operation and high amplitude modulation. The proposed 3 ACQW structure showed the lowest operating voltage, while maintaining high absorption modulation. The CCMC with 3 ACQW structure also showed high amplitude modulation (>50%) and a wide spectral bandwidth of over 8 nm at the operating voltage of only -8 V, which is about 41% lower in operating voltage. This low voltage operation of EAM with 3 ACQW structure also resulted in a 65% lower power dissipation compared to that of EAM with RQW structure. These results indicate that EAM with the proposed 3 ACQW are highly promising for the realization of full HD 3D imaging system.

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References

[1] R. Schwarte, H.-G. Heinol, Z. Xu, and K. Hartmann 1995 *Proc. SPIE* **2588** 126-134
[2] B. Saleh and M. Teich 1991 *John Wiley & Sons* ISBN 0-471-83965-5
[3] M. Kawakita, K. Iizuka, H. Nakamura, I. Mizuno, T. Kurita, T. Aida, Y. Yamanouchi, H. Mitsumine, T. Fukaya, H. Kikuchi, and F. Sato 2004 *Opt. Express* **12** 2781-2794
[4] Y. H. Park, Y. C. Cho, J. W. You, C. Y. Park, H. Yoon, S. H. Lee, J. O. Kwon, and S. W. Lee, B. H. Na, G. W. Ju, H. J. Choi, and Y. T. Lee 2013 *J. Micro-Nanolithogr. Mems. Momes.* **12** 023011

[5] T. K. Woodward, J. E. Cunningham, and W. Y. Jan 1995 *J. Appl. Phys.* **78** 1411-1414
[6] Y. C. Chan and K. Tada 1991 *IEEE J. Quantum Electron.* **27** 702-707
[7] H. Feng, J. P. Pang, M. Sugiyama, K. Tada, and Y. Nakano 1998 *IEEE J. Quantum Electron.* **34** 1197-1208
[8] M. F. Krol, R. P. Leavitt, J. T. Pham, B. P. McGinnis, and N. Peyghambarian 1995 *Appl. Phys. Lett.* **66** 3045-3047
[9] Y. J. Chen, E. S. Koteles, B. S. Elman, and C. A. Armiento 1987 *Phys. Review B* **36** 4562-4565
[10] D. Atkinson, G. Parry, and E. J. Austin 1990 *Semicond. Sci. Technol.* **5** 516-524
[11] N. Debbar, S. Hong, J. Singh, and P. Bhattacharya 1989 *J. Appl. Phys.* **65** 383-385
[12] Y. Chiu, S. Z. Zhang, V. Kaman, J. Piprek, and J. E. Bowers 2001 *Proc. SPIE* **4490** 1-10
[13] B. H. Na, G. W. Ju, H. J. Choi, Y. C. Cho, Y. H. Park, and Y. T. Lee, 2012 *Opt. Express* **20** 19511–19519