CHAPTER V

CONCLUSIONS

In the framework of research, the simulation for investigating of overall polarization characteristics of InAs linearly aligned QD structure (approximately modeled corresponding to real AFM images by using rectangular shape QDs) under applied electric field system was systematically studied. By using two-dimensional time-independent Schrödinger equation implemented by the finite difference method (conform with numerical approximation), the polarization degree was successfully calculated. For external applied electric field system, two-dimensional Laplace's equation solved numerically with the same finite difference method provided more realistic electric field distribution of the system (adjusted via axially applied voltage). Calculation of both polarization degree and applied electric field were verified by comparing the results between Matlab® programming language and COMSOL Multiphysics in order to confirm an accuracy of calculation. The other effects such as finite offset, ratio of band offset, and effective mass of carriers were all taken into account. Then, the aligned QD system was combined with the applied electric field system to demonstrate the QCSE on polarization degree.

The polarization study in the absence of electric field was first examined. For isotropic single QD, there is no polarization anisotropy due to identical optical intensity in all directions. A certain degree of polarization is obtained when the dot is elongated in one direction and can be enhanced by increasing its aspect ratio. For aligned QD structure, the overlapping of carrier wavefunctions (from individual QDs) between adjacent dots is represented by the **"overlap integral"**, which is an important factor used to calculate the polarization anisotropy. As the number of QDs increases, coupling strength also increases (more overlapping region from additional QDs), giving rise to higher polarization degree. The polarization degree strongly depends on spatial separation between adjacent dots. When the interdot spacing is smallest (thinnest barrier between adjacent dots), aligned QDs act like a quantum wire (all multiple quantum wells converge to a single longer potential well), and the highest degree of polarization is thus obtained. In view of size effect on the polarization degree, larger isotropic QDs in the alignment show a small amount PD which originates from the localization of wavefunctions in the dot region so that overlapping of adjacent dots reduces. On the other hand, a larger degree of polarization results in the smaller QDs because of larger degree of coupling. These results indicate that a large number of QDs with a small dot size and a very close spacing between adjacent dots is preferred to get a larger polarization degree.

In presence of external applied electric field, some interesting polarization characteristics occur. The applied field in the direction parallel to the direction of elongation or alignment of QDs (or x direction) was chosen for all calculations since this affects on electric field-dependent polarization anisotropy in a larger extent than that in the perpendicular direction. An isotropic QD is able to give a polarization anisotropy as electric field is applied to the system (by resonant tunneling of electron and hole; and the hole wavefunction is used for determining the optical polarization property because its spatial asymmetry is more easily observed). However, polarization in this case remains a small value. Unlike in case of elongated QD, when QD is elongated in one direction, a strong lateral confinement produces a large polarization degree, and even larger with increasing applied field or lateral size of QD. In the view of QD aspect ratio, larger QDs give a higher polarization degree because of the larger asymmetry (from lower confinement) for fixed aspect ratio, and QD with high aspect ratio also exhibits a large polarization degree (the more elongated structure, the larger electric field-induced anisotropy is obtained). It is essential to optimize between the size effect and the electric field strength by properly keeping the aspect ratio, which is related to both width and height of QD with a suitable magnitude of electric field for obtaining a strong polarization degree.

Extending from single QD to the case of more complicated structure or aligned QD system, our calculations render distinguished results from this structure, demonstrating an interesting electric field-dependent polarization property. In the low applied electric field, polarization degree gradually increases with increasing applied field, and rapidly goes up at the intermediate field magnitude which gives rise to a larger amount of PD before reaching the maximum PD value at $V_{PD(\max)}$. This tendency reflects a good behavior of the optical anisotropy with respect to the increase of applied field (especially the $V_{PD(\max)}$, which is needed for utilizing as "operating point" of the system of optical devices.) Besides, polarization degree in this structure can be compared to large lateral size of elongated structure (because it is also able to produce a strong polarization degree), and used to design the real structure to be grown (in practice, overlarge lateral size of elongated QD structure is difficult to grow). Unfortunately when applied voltage was larger than $V_{PD(\max)}$, polarization degree turns to decrease, which was attributed to increasing of transition probability in the direction perpendicular to the aligned QD direction (activated by the effect of larger kinetic energy and thermal energy). At the condition of strong applied field, the effect of $V_{breakdown}$ drastically reduces the polarization degree (implying an unstable operating state). Furthermore, the higher number of QDs not only increases the degree of polarization, but also leads to a shift of $V_{PD(\max)}$ to lower voltage which implies a use of lower applied field. By contrast, it creates a more sharply decreasing of PD than in case of low number of QDs when a strong field was applied. These results can be interpreted that the level of applied electric field strongly influences the variation of polarization degree, which is essential to determine the apppropriate optical anisotropy.

The effect of interdot spacing on this aligned QD structure under externally applied electric field can be successfully predicted. An applied electric field is insufficient to increase a polarization degree in case of large spacing between QDs (small interaction of carrier coupling). On the other hand, very close distance between QDs addresses an important quantum mechanical effect for the aligned QD to exhibit more a quantum-wire-like behavior, resulting in great polarization degree (closely related to strong overlap integral).

Larger size of aligned QDs makes the polarization degree to decrease when the applied field increases. One possible reason describing this result is the more localization of carrier wavefunctions in individual QDs, which leads to a reduced extent of overlapping with adjacent QDs, which in turn limits the degree of polarization.

All calculated results reveal that the variation of polarization degree depends on four intrinsic factors: QD size, interdot spacing, electric field strength, and number of QDs. Among these, the crucial factor which mostly affects the polarization degree is the "**interdot spacing**" between QDs (due to its high impact on the variation of the overlap integral and the PD value). In addition, those other factors mentioned above are always considered concurrently with interdot spacing for improving the polarization degree to become as high as possible.

Even though the aligned QD model used in the thesis work gives excellent acceptable results of optical behaviors, it stills has some limitations in the calculations. First, the QD structure was approximated by a simple form. Secondly, recognize that the accuracy of calculation by numerical method comes from the higher number of grid points. Matlab® programming shows "out of memory" when running too large matrix. In case of COMSOL Multiphysics, this program is easier to use for running the calculations (it also has various models for implementation) and gives higher accuracy, but less flexible than the Matlab® programming in case of advance-level analysis. The possible alternative ways for solving this problem is to use a high-efficiency computer, to change to other calculating programs such as C++, ABAQUS, and other programs which is compatible with the Matlab®, or to use the finite element method (because the number of grid points can be reduced, compared with the finite difference method).

In terms of applications, there are various semiconductor optical devices potentially employing aligned QD structures driven by applied electric field, such as polarization-sensitive optical modulators/converters **[232]** (high potential of data encoding and decoding), polarization-sensitive switches/filters **[234]** (high speed switching), polarization-sensitive photodetectors **[223, 233]** (needed in secure optical data communications and optical networks), strong coherent aligned-QD laser **[139, 167]** [high efficiency of emission intensity (with minimum loss) coming from polarization tunability with assistance of electric field], polarization computing devices like quantum cellular automata **[234]** (by electron-tunneling effect between dot and coulomb repulsion related to arrangement of electrons as many types of logic gate (AND, OR, ,XNOR, NAND, NOR, XNOR, NOT) with powerful performance), etc.

Investigation of optical properties from an aligned QD structure under applied electric field reveals a lot of valuable information both physical meanings (the study of QCSE regarding the polarization degree provides us with a wealth of knowledge about how electric field affects the dynamics of carrier coupling and variation of polarization anisotropy) and applications (these new results help us to broaden the intellectual horizon of novel ideas in view of utilizing them in designing with high-efficiency semiconductor optical devices. In the end, a good polarization property remains one of the important characteristics required for efficient semiconductor optical devices based on QD structure (the other important characteristics include strong emission intensity, defect free, dot size homogeneity, and temperature insensitive property).

In future work, we plan to grow the aligned QD structure and experimentally investigate the effect of electric field on polarization property. Simulation of this structure is also calculated for comparing between experimental and theoretical results. Other effects such as alloy profiles, wetting layer, spintronics, intensive Coulomb interaction, anti-crossing, valence band mixing, excited-state relation, three-dimensional structure, strain field, and temperature, may be included to get more precise results.