Characterization of heavy masses of two-dimensional conduction subband in InGaAs/InAlAs MQW structures by pulsed cyclotron resonance technology

CONF-980729--

N. Kotera^a, H. Arimoto^b, N. Miura^b, E. D. Jones^c, K. Tanaka^a, T. Mishima^d, and M. Washima^e^aKyushu Institute of Technology, Iizuka City, FUKUOKA 820-8502, Japan^bInstitute of Solid State Physics, University of Tokyo, Roppongi, TOKYO 106, Japan^cSandia National Laboratories, Albuquerque, NEW MEXICO 87185-0601, USA^dCentral Research Laboratory, Hitachi Ltd., Kokubunji, TOKYO 185, Japan^eAdvanced Research Center, Hitachi Cable, Ltd., Tsukuba City, IBARAKI 300, JapanRECEIVED
JUN 02 1998
OSTI

ABSTRACT

Conduction-band effective masses in a direction parallel to the quantum well plane were investigated in n-type-modulation-doped InGaAs/InAlAs multi-quantum well system. Thicknesses of well and barrier were 5 and 10 nm. Three highly-doped specimens having about $1 \times 10^{12} \text{ cm}^{-2}$ per one quantum well were prepared by MBE. Double-crystal X-ray diffraction was used to check the crystal quality. Heavy electron effective masses, almost 50%-bigger than the band edge mass of $0.041m_0$, were measured by far-infrared and infrared cyclotron resonances under pulse high magnetic fields up to 100 T. Nonparabolicity of this subband was less than 12% by comparing the two cyclotron resonances. Observed two-dimensional subband structure was quite different from conduction-band effective mass in a direction perpendicular to the same quantum well and from GaAs/GaAlAs quantum well system.

Keywords: infrared, far infrared, cyclotron resonance, effective mass, quantum well

1. INTRODUCTION

As one of optoelectronic materials, InGaAs is widely used for 1.5-micron-band lasers and photodetectors. Electronically, square potential wells confining electrons and holes in an InGaAs layer can be formed in $\text{In}_x\text{Ga}_{1-x}\text{As}/\text{In}_y\text{Al}_{1-y}\text{As}$ multi-quantum wells (MQWs). When $x=0.53$ and $y=0.52$, those materials can be lattice-matched to the wafer substrate, InP, and this eases growing MQW structures on InP. Heavy doping of impurities are normally used in optoelectronic devices. InGaAs semiconductors with the relatively narrow band gap of $0.74 \text{ eV}^{1,2,3}$ are expected to have nonparabolicity in the conduction subbands⁴ and band-gap renormalization due to heavy doping.⁵ Electron effective mass will depend on the kinetic energy⁶ and well thickness.⁷ Physical data in QWs stated above were mostly taken using GaAs/GaAlAs MQW system. Data and analysis on InGaAs/InAlAs MQW system are quite few.

So far, electron effective masses in InGaAs were measured using bulk crystals and $\text{In}_{0.53}\text{Ga}_{0.47}\text{As}/\text{InP}$ hetero-interfaces. In the latter case, two-dimensional (2D) electrons are confined within the triangular potential well at the interface. The cyclotron mass was reported to be $0.047m_0$ at low temperatures^{8,9}. In early stages of research, 2D effective mass in $\text{In}_{0.53}\text{Ga}_{0.47}\text{As}/\text{In}_{0.52}\text{Al}_{0.48}\text{As}$ MQWs was estimated to be $0.05m_0$ from temperature dependence of Shubnikov-de Haas oscillations at low temperatures.¹⁰ Well thickness was ranging from 3 to 8 nm. The carrier concentration was about 10^{11} cm^{-2} . In $\text{In}_{0.53}\text{Ga}_{0.47}\text{As}/\text{In}_{0.52}\text{Al}_{0.48}\text{As}$ MQW systems with well thickness of 5-20 nm, two to seven discrete eigen states appeared in the conduction subbands within the well having the band offset of about 0.5 eV^{11-15} .

In this report, effective mass of conduction electrons was investigated in three different n-type modulation-doped $\text{In}_x\text{Ga}_{1-x}\text{As}/\text{In}_y\text{Al}_{1-y}\text{As}$ MQW specimens using pulse cyclotron resonance techniques in very high magnetic fields. Crystal structures, 2D electronic nature of the bands, and a kind of carriers were checked by X-ray diffractions, interband optical transmission, and transport measurements. Data were taken at 6- and 60-T range and compared to derive effective masses at different electron energies. Conduction-band nonparabolicity and big 2D-effective mass were discussed.

N. Kotera: E-mail: kotera@csc.kyutech.ac.jp; Telephone: +81-948-29-7668; Fax: +81-948-29-7688
K. Tanaka: E-mail: tanaka@cancer10.csc.kyutech.ac.jp; Telephone: +81-948-29-7688

Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy under contract DE-AC04-94AL85000.

2. EXPERIMENTAL PROCEDURES

2.1. Sample Fabrication

Specimens measured were cut from an epitaxial wafer grown by MBE on a (100) surface of a Fe-doped InP substrate. The wafer was composed by an undoped InAlAs buffer layer on InP, InGaAs/InAlAs MQW layers, and an undoped InAlAs cap layer on top.

M5 specimen had 99 pairs of InGaAs wells with the thickness of 5 nm (5 nm well) and adjacent InAlAs barriers with the thickness of 10 nm (10 nm barrier). Si doping with a density of 10^{18} cm^{-3} in 10-nm-thick barrier produced $1 \times 10^{12} \text{ cm}^{-2}$ electrons in one QW (process control target). Doping was made homogeneously in InAlAs barriers without spacer layers in them. On top of 99 MQW layers, one 10-nm-thick InGaAs layer was formed so as to have the same carriers in it. Total MQW thickness was 1510 nm. Interband optical transmission, cyclotron resonance, and transport measurements are mostly related to the 99 MQW layer of 5-nm-thick InGaAs layers. Magneto-photoluminescence could show a signal from the top surface well of 10-nm thickness. Detailed fabrication procedures were given elsewhere,¹⁶ showing magneto-photoluminescence analysis of 10 nm InGaAs well.

An MBE machine different from the one used for M5 was used for fabricating M10L and M10H wafers. Various kinds of specimens were needed to check the magnitude of effective masses in nanoscale InGaAs QWs. M10L specimen had 40 pairs of 10 nm wells and 14 nm barriers, comprised by doped 10-nm-thick layers sandwiched by 2-nm-thick undoped spacer layers. Total MQW thickness was 960 nm. Doping control target of Si was one half of M5 to get $5 \times 10^{11} \text{ cm}^{-2}$ electrons per one QW.

M10H specimen had 20 pairs of 10 nm wells and 14 nm barriers with the same spacer layers as above. Total MQW thickness was 480 nm. Doping control target of Si was three halves of M5 to get $1.5 \times 10^{12} \text{ cm}^{-2}$ per one QW.

2.2. Cyclotron Resonance Technologies

As a radiation source of the FIR cyclotron resonance, a methanol laser of a wavelength, λ , of 119 μm excited by a CO_2 laser (119 μm light source) was used. The light was introduced normally to the specimen surface, or to the QW plane. A pulse magnetic field of millisecond duration up to 13 T was applied normal to the specimen surface.

The transmission ratio (magneto-transmission), the ratio of a light transmission in a magnetic field to that of zero field, was measured in this technique. The magneto-transmission of the circular polarized light was plotted against the increasing and decreasing magnetic field during the one-shot pulse, using a cooled Ge detector. Unpolarized light was once used but, at low temperatures, magneto-transmission curves showed only increasing tendencies when magnetic field was increased. The curve had a slight dip in a wide magnetic field range, near room temperature.

Use of electron-sensitive polarized light removed this difficulty and the curves became V-shaped at the resonance. Cause of this phenomenon will be due to unknown excitations of localized states and magnetic freeze out. Localized centers like donors in buffer layers or interfaces might have activation energies near 10 meV that is very close to the energy, 10.4 meV, of 119 μm light source. At high magnetic fields, the activation energy became larger and specimens became more transparent for this FIR radiation.

As the radiation source of IR cyclotron resonance, a CO_2 laser of wavelengths, λ , of 10.6 μm (10.6 μm light source) was used and combined with a pulse magnetic field of microsecond duration up to a maximum of 150 T. Configuration of specimens, light, and magnetic field was the same with the above. Used photon energy was as large as 117 meV. Sizes of the well and the barrier layers were much smaller than the IR wavelengths used.

3. MEASURED RESULTS FOR CHARACTERIZATION

3.1. X-Ray Diffraction Measurements

To check the crystal quality, double-crystal X-ray diffraction of the fourth order was measured at room temperature. X-ray source was a line from Cu target, $\text{K } \alpha_1$, where $\text{K } \alpha_2$ line was mostly cut by Ge reflector. The X-ray wavelength was 0.154 nm. Angle of a very sharp reflection peak caused by a substrate, InP, (InP peak) was set to be 31.656 degrees in this analysis. A center peak associated with several satellite peaks were assigned to come from MQW layer (MQW peak), as seen in Fig. 1.

Period of the MQW layer or the total thickness of one well and one barrier was deduced from the average of angle separation between satellite peaks. All the MQW periods in M10L, M5, and M10H were very close to the nominal

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

Figure 1. Double-crystal X-ray diffraction spectrum at room temperature for a specimen, M10L.

period or the process control target, as shown in Table 1. Well thicknesses were also obtained by proportional calculations. M10L and M10H had the well thicknesses of 10 nm, while M5 had the thickness of 5 nm.

The angle difference between the InP and the MQW peaks determined the composition, x , of the $\text{In}_x\text{Ga}_{1-x}\text{As}$. A composition for lattice matching was assumed $x=0.532$ in this calculation. Shift of x from the matching condition in M10H was big among three specimens and the excess of Ga will induce the mass increment, compared with the lattice-matched one. The correction factor is easily deduced. Mass difference of GaAs and InAs is $0.041m_0$, which is the amount when x changes from 1 to 0. This simple correction is reasonable because the average of the masses is almost $0.041m_0$ and this is the known band-edge mass of $\text{In}_{0.53}\text{Ga}_{0.47}\text{As}$.

3.2. Electrical Measurements

According to Hall effect measurements of Pauw geometry specimens, active carriers in M5 were found to be electrons. The sheet carrier concentration per one QW was estimated to be $0.8\text{--}1.0 \times 10^{12} \text{ cm}^{-2}$ between room temperature and 77 K. Electron mobility in the narrow InGaAs QW was 4.3×10^3 and $6.4 \times 10^3 \text{ cm}^2/\text{Vs}$ at room temperature and 77 K, respectively. This mobility was smaller than that of GaAs/GaAlAs MQWs, by a factor of $10^2\text{--}10^3$.

For low-temperature transport experiments, the M5 chip was patterned and mesa-etched to get a Hall bar. At 1.5 K and a constant current of $1 \mu\text{A}$, Hall voltage and resistive voltage were measured as a function of magnetic field. The resistance curve had several peaks of Shubnikov-de Haas oscillations. One minimum at 6.78 T corresponded to the filling factor of 6 in Landau levels. From the oscillation period, sheet electron concentration was determined to be $0.98 \times 10^{12} \text{ cm}^{-2}$ that was the same with the process control target. The Hall resistance for 99 layers was 43Ω . Thus Ohmic contacts were connected to 99 QW layers in this chip.¹⁷

Table 1. Summary of X-ray diffraction measurements for specimens, M10L, M5, and M10H.

sample	period nominal	period measured	well thickness	composition shift (excess)	angle shift from InP
M10L	24 nm	23.8 nm	9.9 nm	0.005 (In)	-0.012 deg
M 5	15 nm	14.4 nm	4.8 nm	0.023 (In)	-0.057 deg
M10H	24 nm	23.6 nm	9.8 nm	-0.038 (Ga)	+0.093 deg

Figure 2. Interband optical transmission spectrum at 140 K for specimens, M10L, M10H, and U10.

3.3. Optical Transmission Measurements

Infrared interband transmission was measured at 140 K in the energy range of 0.8 and 1.5 eV, using a Halogen lamp and a MIC3 (Jobin Yvon) grating monochromator. Light was introduced on the MQW surface of M10L and M10H specimens. Transmitted light was detected with a commercial InGaAs detector. The curves shown in Fig. 2 are normalized ones with the light intensity without specimens. An undoped specimen named U10, which had 10 period of 10 nm wells and 10 nm barriers, was used as a reference. Well thickness determined by X-ray diffraction was 10.6 nm in this case.

As shown in Fig. 2, whole the 10 nm well specimens had three dips at similar energies marked by a, b, and c. Noise in the spectrum near 0.9 eV was caused by the gratings and should be ignored. Interband transitions, a, b, and c, were assigned to be allowed transitions from heavy hole (HH) eigen-states, HH_n , to conduction subband (CB) eigen-states, CB_n , where n was the quantum number and $n=1, 2$, and 3 in this case. Energy separation between dips were comprised by sum of eigen-energies of electrons and holes. Because HH eigen-energies are much smaller than CB eigen-energies, the spectrum showed that three conduction subbands were included in the QW¹¹⁻¹⁵

Calculated Fermi energies at 140 K were 17 and 60 meV for the M10L and M10H specimens, if the density-of-state mass of $0.06m_0$ is assumed. This mass was obtained from the cyclotron resonance experiments described later. Corresponding electron concentrations of the specimens were taken as $5 \times 10^{11} \text{ cm}^{-2}$ and $1.5 \times 10^{12} \text{ cm}^{-2}$, respectively. The blurred spectra in the HH1 to CB1 transition were caused by the presence of Fermi level in the ground subband. These experiments clearly showed the presence of electron gas in the ground conduction subbands in M10L and M10H.

4. IR CYCLOTRON RESONANCE IN 60-T RANGE

The $\omega_c \tau$ calculated from mobility was about 1 for 2 T and sharp resonance absorption was expected in a magnetic field more than 10-20 T, where ω_c is the cyclotron angular frequency and τ is a momentum scattering time. The quantum limit condition is reached above 20 T when the carrier concentration was $1 \times 10^{12} \text{ cm}^{-2}$, where the Fermi level laid within the ground Landau level. Calculated Fermi energies in zero-magnetic field, assuming the constant density-of-state mass of $0.06m_0$ at room temperature, were 3, 34, and 55 meV for M10L, M5, and M10H, respectively.

Infrared magneto-transmission using a $10.6 \mu\text{m}$ light source was measured at room temperature by varying magnetic fields, B . As shown in Fig. 3 (a) and Fig. 3 (b), the transmission ratios using an unpolarized light had a clear minimum at 59 T, for M10L and M10H. Double traces in Fig. 3 showed the pulse responses for increasing and decreasing magnetic fields. Data of M5 were taken in the same way.¹⁷

Figure 3. (a) Infrared magneto-transmission using 10.6 micron wavelength by cyclotron resonance at room temperature, for a specimen, M10L.

To supplement checking 2D nature of the subbands, cyclotron resonance experiments using a tilted specimen was made. Only the normal component of the magnetic field, $BCOS\theta$, will induce the resonance in 2D QWs. Experiments showed that the resonance field changed as $(COS\theta)^{-1}$ between the angle of zero and about 40 degrees where the normal incidence was set to be the zero.

Apparent effective mass, m_{app}^* , deduced from $h\nu = \hbar eB/m_{app}^*$ was $0.59m_0$, where $h\nu$ is a photon energy and e is the electronic charge. When we correct the composition shift of x due to In or Ga excess described before, the mass values were obtained as shown in Table 2. The amount of correction is also shown in Table 2. Spin splitting was not

Figure 3. (b) Infrared magneto-transmission using 10.6 micron wavelength by cyclotron resonance at room temperature, for a specimen, M10H.

Table 2. Measured results of cyclotron resonances at room temperature for specimens, M10L, M5, and M10H. Two-dimensional conduction-subband effective masses are listed for high-energy electrons and low-energy electrons. Mass increment ratios are the measure of nonparabolicity of the bands.

sample	m_{app}^* at 10.6 μm	$m^*(0)$ at 119 μm	$m^*(1)$	correction by x shift	$\{m^*(1)-m^*(0)\}$ / m_0
M10L	$0.059m_0$	$0.050m_0$	$0.056m_0$	0.0002	12%
M 5	$0.067m_0$	$0.060m_0$	$0.065m_0$	0.0009	8%
M10H	$0.057m_0$	$0.056m_0$	$0.057m_0$	-0.0016	2%

observed up to 150 T in M5.¹⁸

Not like a conventional cyclotron resonance, the photon energy which is equal to the Landau transition energy is 117 meV for 10.6 μm wavelength. Therefore, the apparent mass defined above is not a simple cyclotron mass. The mass of the ground Landau level, $m^*(0)$, and the mass of the first higher Landau level, $m^*(1)$, should be treated separately. Those values should be different if the 2D conduction subbands were nonparabolic. Estimation of the two masses will be given in the next section.

5. FIR CYCLOTRON RESONANCE IN 6-T RANGE AND ANALYSIS

Infrared magneto-transmission using a 119 μm light source was measured at room temperature by varying magnetic fields below 30 T, as shown in Fig. 4 (a) and Fig. 4(b). Electron-sensitive circular polarization was used for this experiment for the reason described in Section 2.2. The transmission ratios using a polarized light had a minimum at 4.4-4.5 T for M10L and at 5.1-5.2 T for M10H. Those ambiguities came from experimental errors determining a minimum in the curves, or from broadening of the cyclotron absorption.

Magneto-transmission at zero-magnetic field was defined to be one, here. It should be noted that cyclotron absorption tail was extended to negative magnetic field corresponding to hole-sensitive polarization. This is the case when broadening is large in circular polarization experiments. Fermi energies for those specimens were between 3 and 55 meV and the thermal broadening was about 100 meV at 300 K. When $B=5$ T, Landau level separations were almost 10 meV and 10 to 15 Landau levels including both spins were occupied by the thermal electrons for M10L,

Figure 4. (a) Far-infrared magneto-transmission using 119 micron wavelength by cyclotron resonance at room temperature, for a specimen, M10L.

Figure 4. (b) Far-infrared magneto-transmission using 119 micron wavelength by cyclotron resonance at room temperature, for a specimen, M10H.

M5, and M10H specimens. At zero temperature, a single Landau level can accommodate $2.4 \times 10^{11} \text{ cm}^{-2}$ electrons and 7, 5, and 3 Landau levels have to be occupied. Therefore, effective masses in our measurements were the averages of those conduction electrons occupied in many Landau levels. It must be assumed that the effective masses of concerned Landau levels are to be the same. The results are also shown in Table 2 as a low-energy effective mass, $m^*(0)$. Correction by the excess In or Ga was also made.

If the low-energy effective masses are given, we can estimate a high-energy effective mass written as $m^*(1)$ in Table 2. In cyclotron resonances using $10.6 \mu\text{m}$ light sources, the above $m^*(0)$ is regarded as the mass of the ground Landau level. By assuming $m^*(0)$, we can deduce the mass, $m^*(1)$, at the first higher Landau level from the measured apparent mass, m_{app}^* , by an equation, $3/m^*(1) = 2/m_{app}^* + 1/m^*(0)$. Obtained high-energy masses are also tabulated in Table 2. The mass increment ratio, $\{m^*(1) - m^*(0)\}/m_0$, can be regarded as a measure of nonparabolicity in the 2D conduction subbands and also tabulated in Table 2.

Magneto-photoluminescence of M10H was successfully measured at 1.4 K and five optical transitions were assigned. Experimental arrangements were described elsewhere.¹⁶ Conduction-subband Landau-level energy changed from 0 to 25 meV as a function of magnetic field below 13 T. Deduced electron mass was $0.061m_0$ experimentally. After the correction for x shift, the 2D bandedge mass was $0.059m_0$. This was very close to the value at room temperature in Table 2.

The low-energy mass, $m^*(0)$, in M10L agrees with that of Stolze's paper.¹⁰ By comparing with M10H, the mass had an increasing trend with the carrier concentrations. By comparing the mass of M5, the effective mass increased when the well thickness increased. The mass increment ratios of the specimens decreased from 12% to 2% as the electron concentration increased, so the subband structure might be affected by the number of carriers in QWs. The high-energy mass, $m^*(1)$, seemed independent of carrier concentrations. The mass value is almost $0.06m_0$ and this is 50%-larger than the bulk band-edge mass of $0.041m_0$. In 5-nm thick QWs, the effective masses were over $0.06m_0$ and nonparabolicity was unexpectedly small. The normal mass perpendicular to the QW plane had a trend of strong nonparabolicity in spite of the above experimental results.¹² In-plane nonparabolicity in InGaAs/InAlAs MQWs is quite different from that of GaAs/GaAlAs MQWs.

6. CONCLUSION

In-plane electron effective masses parallel to the QW plane were investigated using InGaAs/InAlAs MQW specimens with different carrier concentrations of about $1 \times 10^{12} \text{ cm}^{-2}$. Two kinds of cyclotron resonances with different resonance photon energies were compared and the low-energy mass and the high-energy mass were deduced. The

mass value was compared with the result of magneto-photoluminescence. Effective masses were much heavier than the reported before, when the electron concentration was increased near $1 \times 10^{12} \text{ cm}^{-2}$. The 2D band-edge mass for 10-nm-thick InGaAs well was $0.050m_0$ - $0.056m_0$ at room temperature. The 2D band-edge mass for 5-nm-thick InGaAs well was $0.060m_0$. Band nonparabolicity or the increment of mass at high energy was found to decrease when carrier concentration was increased. The amount of mass increment was as small as 12% or less, even the kinetic energy of conduction electron was high above 117 meV.

7. ACKNOWLEDGMENTS

The authors were grateful to Mr. H. Nakamura of Central Research Laboratory, Hitachi Ltd. for advices on quantum-well evaluations and sample fabrication of U10 by MBE.

The authors were grateful to Mr. H. Sakaguchi and Dr. S. Takahashi of Advanced Research Center, Hitachi Cable Ltd. for advices in Hall effect measurements and double-crystal X-ray diffraction. The authors were indebted to Dr. K. Higuchi and Mr. M. Komori for selective etching and surface structure evaluation.

The authors were indebted to Dr. T. Takamasu and Mr. M. Ohno of Institute of Solid-State Physics, University of Tokyo, for quantum transport measurements.

REFERENCES

1. S. Adachi, *Physical Properties of 3-5 Semiconductor Compounds-InP, InAs, GaAs, GaP, InGaAs, and InGaAsP*, p.86 (A Wiley-Interscience Publication, 1992).
2. O. Madelung, *Semiconductors-Basic Data*, p.154 (Springer, 1996).
3. P. Bhattacharya, *Properties of Lattice-Matched and Strained Indium Gallium Arsenide*, p.206 (An INSPEC publication, 1993).
4. U. Ekenberg, Phys. Rev. B **40** (11) 7714(1989-I).
5. D. A. Kleinman and R.C. Miller, Phys. Rev. B **32** (4) 2266(1985).
6. M. A. Hopkins, R. J. Nicholas, M. A. Brummel, J. J. Harris, and C. T. Foxon, Phys. Rev. B **36** (9) 4789(1987-II).
7. K. Suzuki, K. Saito, T. Saku, A. Sugimura, Y. Horikoshi, S. Yamada, J. Crystal Growth **150** 1266 (1995).
8. Y. Guldner, J. P. Vieren, P. Voisin, M. Voos, M. Razeghi, and M. A. Poisson, Appl. Phys. Lett. **40** 10877 (1982).
9. P. Maurel, M. Razeghi, Y. Guldner, and J. P. Vieren, Semicond. Sci. Technol. **2** 695 (1987).
10. W. Stolz, J. C. Maan, M. Altarelli, L. Tapfer, and K. Ploog, Phys. Rev. B **36** (8) 4310 (1987-II).
11. N. Kotera, K. Tanaka, and H. Nakamura, J. Appl. Phys. **78** (8) 5168 (1995).
12. K. Tanaka, N. Kotera, and H. Nakamura, Appl. Phys. Lett. **68** (5) 649 (1996).
13. K. Tanaka and N. Kotera, Institute of Physics Conference Series No.145: Chapt.3, p.455 (Paper presented at the twenty-second International Symposium on Compound Semiconductors, Cheju Island, August, 1995).
14. N. Kotera and K. Tanaka, Institute of Physics Conference Series No.145: Chapt.3, p.393 (Paper presented at the twenty-second International Symposium on Compound Semiconductors, Cheju Island, August, 1995).
15. K. Tanaka and N. Kotera, *Proceedings of the Eighth International Conference on Indium Phosphide and Related Materials* (IEEE catalog No.96CH35930) p.622.
16. E. D. Jones, N. Kotera, T. Mishima, H. Nakamura, N. Miura, and C. P. Tigges, *Proceedings of SPIE Physics and Simulation of Optoelectronic Devices V*(February 10-14, 1997, San Jose, California), 2994 460(1997).
17. N. Kotera, E. D. Jones, K. Tanaka, H. Arimoto, M. Ohno, N. Miura, T. Mishima, Y. Shimamoto, K. Komori, K. Higuchi, *Proceedings of the Eighth International Conference on Narrow-Gap Semiconductors* (Shanghai, China, April 21-24, 1997), to be published.
18. N. Kotera, Y. Shimamoto, T. Mishima, N. Miura, Physica B **227** 349 (1996).

M98005452

Report Number (14) SAND -- 97-3155C
CONF-980729--

Publ. Date (11) 199805
Sponsor Code (18) DOE/DP, XF
UC Category (19) UC-700, DOE/ER

19980706 045

DOE