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IR lasing scheme on X-Γ transitions under real space transfer in n-type GaAs-AlAs-like MQW heterostructures

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Abstract. New mechanism for IR laser action on transition between X-valley states in AlAs and Γ valley states in GaAs under Γ-X intervalley transfer in GaAs and X valley GaAs-AlAs real space transfer is proposed. Ratio of occupation numbers in X-valleys to the numbers in Γ could be higher than 100 while amplification coefficient could be as high as 100 cm^{-1}. In $Ga_xAl_{1-x}As$-$Ga_yAl_{1-y}As$ MQW system, $x < 0.4$, $y > 0.4$ by changing composition the laser tunability from 3 μm to 100 μm could be achieved.

Introduction

There is a need to find out a scheme which can provide lasing in simple MQW systems which could fill band from far to mid IR regions. Recently our group came across [1, 2] seems a universal population inversion mechanism based on RST in MQWs and lower heating (providing lower electronic temperature) of the higher laying states which could serve this goal. In particular it was pointed out [2] that the mechanism should work under mixture of intervalley and RST in n-type GaAs-AlAs-like MQWs. And the present report gives thorough discussion of the latter possibility.

1 X–Γ valley population inversion

In GaAs-AlAs MQW system the conduction band structure is such (Fig. 1a) that GaAs layers are wells for Γ-valley electrons while AlAs layers are wells for X-valley electrons. If GaAs thickness is not so low then the Γ-valley level in GaAs is lower than X-valley lowest level. Under high enough electric field Γ-valley electrons reach energy higher than X-valleys in GaAs and perform Γ-X intervalley transfer (IVT). Then moving spatially in X-valleys electrons perform RST to AlAs layers, "fall down" to lowest X-valley level in AlAs due to optical and intervalley phonon scatterings and are accumulated at the level due to low rate of X–Γ transfer through GaAs-AlAs interface (Fig. 1b). The rate is low due to low density of states (effective mass) and to low overlapping of X and Γ valley wave functions and weak direct X–Γ coupling at the interface (cf. e.g. [3, 4]) All these result in reduction of X–Γ intervalley scattering element to $\delta \leq 10^{-2}$ as compared with the element inside GaAs. Also electrons "leak" from GaAs to AlAs due to weak Γ-X scattering through GaAs-AlAs interface. It is this accumulation of electrons at the bottom of X-valleys in AlAs which produces X–Γ valley population inversion.

To give crude estimate of degree of the inversion i.e. ratio of occupation numbers at the bottoms of lowest levels in X and Γ valleys — n_X and n_Γ — let as consider equation

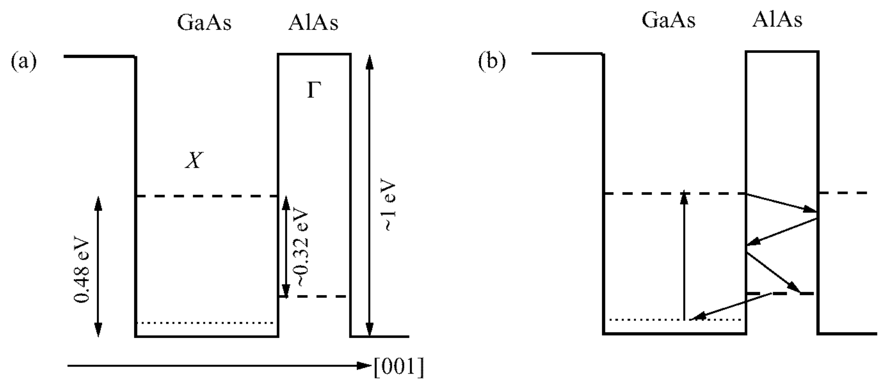

Fig 1. Band diagram of one period of GaAs/AlAs MQWs (a) and scheme of inversion formation process (b).

for total number of electrons in Γ valley of GaAs N_Γ. We suppose that electrons in AlAs occupy lowest level only and they have Boltzman distribution with electronic temperature T_X while Γ electrons on all levels have common electronic temperature T_Γ. We will not consider here contribution of L-valley electrons: AlAs is barrier for L-valleys and in AlAs they are higher in energy than lowest X-valley level; so L-valleys only "suck up" electrons from Γ valley of GaAs increasing degree of the inversion estimated below. The equation for number of electrons in Γ valley may be written approximately as:

$$\frac{dN_\Gamma}{dt} = -\left[\nu_{\Gamma-X}^{\mathrm{GaAs}} \exp\left(-\frac{\Delta_{\Gamma-X}^{\mathrm{GaAs}}}{T_\Gamma}\right) + \nu_{\Gamma-X}^{I} \exp\left(-\frac{\Delta_{\Gamma-X}^{I}}{T_\Gamma}\right)\right] N_\Gamma + \nu_{X-\Gamma}^{I} N_X$$

Here $\nu_{\Gamma-X}^{\mathrm{GaAs}}$ is effective Γ-X IVT scattering rate in GaAs, $\nu_{\Gamma-X}^{I}$ is Γ-X scattering rate through GaAs-AlAs interface, N_X is total electron number at the lowest level in AlAs and $\nu_{X-\Gamma}^{I}$ is return rate from AlAs to GaAs through interface, $\Delta_{X-\Gamma}^{\mathrm{GaAs}}$ is valley separation in GaAs and $\Delta_{X-\Gamma}^{I}$ is the separation across GaAs-AlAs interface. Ratios of the rates may be approximately written as:

$$\frac{\nu_{\Gamma-X}^{I}}{\nu_{\Gamma-X}^{\mathrm{GaAs}}} \approx \delta\beta, \qquad \frac{\nu_{X-\Gamma}^{I}}{\nu_{\Gamma-X}^{\mathrm{GaAs}}} \approx \delta\gamma(m_\Gamma/m_X)$$

Here m_Γ, m_X are effective electron masses, $\delta \approx 10^{-2}$ is the mentioned above reduction factor, β is factor of about unity which is determined by 3d–2d difference between scattering to X-valley continuum in GaAs and 2d Γ-X scattering through interface and by number of X-valleys involved while γ (also about 2-4 for the case discussed below) is factor determined in a similar manner. Because for Boltzman distribution occupation numbers $n_\alpha = (\pi\hbar^2/m_\alpha T_\alpha)N_\alpha$, $\alpha = \mathrm{X}, \Gamma$ for the steady state from the equation (1)–(2) one have:

$$\frac{n_X}{n_\Gamma} \approx \frac{(T_\Gamma/T_X)[\exp(-\Delta_{\Gamma-X}^{\mathrm{GaAs}}/T_\Gamma) + \delta\beta\exp(-\Delta_{\Gamma-X}^{I}/T_\Gamma)]}{\delta\gamma}$$

It is well known that in GaAs at electric field of about the Gunn effect threshold ($E \approx 2$–3 kV/cm) the drastic rise in electron temperature appears and the temperature

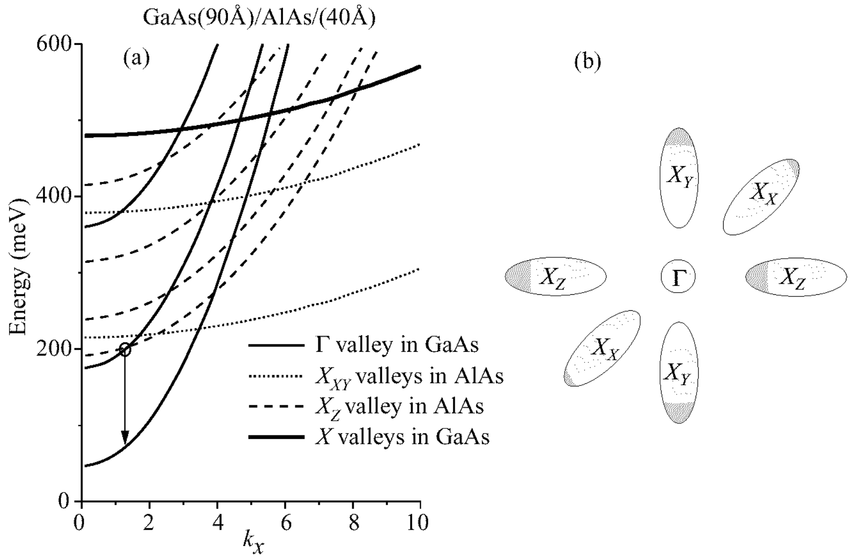

Fig 2. Γ−X valleys in Brilluoin zone of GaAs with *XZ* valleys situated along growth direction (b) and electronic subbands for an example structure.

quickly (at $E \approx 5{-}6$ kV/cm) rise to of about 1/3–1/2 of $\Delta_{X-\Gamma}$ — 100–200 meV. At the same time electronic temperature in X-valleys of AlAs stay low — of about half of energy of an intervalley phonon (15–20 meV) due to strong intervalley scattering. This temperature can be decreased even more if one introduce selectively doping of AlAs. Due to small factor $\delta \leq 10^{-2}$ and high ratio T_Γ/T_X population inversion $(n_X/n_\Gamma > 1)$ is easy achieved here. So we conclude: *In the* GaAs-AlAs MQW *system proposed* X–Γ*-valley population inversion should arise at electric field of about the Gunn effect threshold* $E \approx$ kV/cm *and at higher field can be colossal* — $n_X/n_\Gamma \geq 100$.

It should be also noted that in the field where high population inversion takes place almost all electrons are in X-valleys so that one could expect that there will be no static negative differential conductivity at this field and one can avoid problems related to domain formation.

2 Amplification coefficient

Optical transitions between X and Γ valleys become allowed due to X–Γ-valley coupling at GaAs-AlAs interface for X-valleys — along growth direction (X_z valleys Fig. 2a) — and at resonant conditions when in Γ-valley there is (second) level which has energy close to that of first level in X_z-valleys of AlAs. Also the X_z-valley lowest level should be the lowest in AlAs for the electron accumulation to take place just at these level. Such situation can be achieved at low AlAs layer thickness to provide higher quantizing energy level for the side X_x and X_y valleys. Energy levels in a structure which satisfy all of the mention conditions are given in Fig. 2b.

To estimate amplification coefficient we suppose that all electrons are in X_Z-valleys of AlAs. Amplification coefficient μ for electromagnetic wave propagating along the layers of the MQW structure can be written as:

$$\mu = 4\pi\sigma/\sqrt{\epsilon_0}c, \qquad \sigma = \frac{e^2 N_0 \hbar}{m_X T_X} f$$

Here ϵ_0 is dielectric permeability and σ is the bulk conductivity, N_0 is bulk electron concentration ($N_0 = N_X/d$, $d = d_{GaAs} + d_{AlAs}$ and f is oscillator strength). For 2 to 1 transitions inside GaAs well $f \approx 1$; for resonant X–Γ transition (marked by circle and arrow in Fig. 2b) $f \approx 1/4$ because under resonant coupling independently of the coupling strength wave function are equally divided between two resonantly coupled wells. With $f = 1/4$, $N_X = 5\times10^{11}$ cm^{-2} and $T_X = 20$ meV we get: $\mu = 5\times10^2$ cm^{-1} what is quite a value!

Conclusion

To summarize: we put forward new population inversion and lasing scheme in MQW systems based on X–Γ minima optical transitions from AlAs-like layers to GaAs-like layers under mixture of IVT and RST and present crude estimate of the inversion degree and amplification coefficient for GaAs-AlAs structure which show extremely promising figures for lasing at $\lambda \approx 8\,\mu$m. It should be emphasizes that in the alloy MQW structures $Ga_{1-x}Al_xAs$-$Ga_{1-y}Al_yAs$ with $x < 0.4$, $y > 0.4$ (at x or y equal to 0.4 X–Γ separation is zero in the bulk) there exist broad opportunity for change of the lasing wavelength (both to shorter and to longer wavelength) and also for reduction of electric field needed for lasing. In particular for both x and y close to 0.4 FIR lasing at wavelength longer than say $\lambda \approx 100\,\mu$m could be achieved.

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