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GA based parameter optimizations for better millimeter and sub-millimeter wave response characteristics of GaAs quantum wells

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Abstract : The aim of this work is to predict the optimum values of the system parameters of GaAs quantum wells incorporating the relevant scattering mechanisms for getting better millimeter and sub-millimeter wave response characteristics and to explore the possibilities of new applications of such nanostructures Optimized parameters have been computed by employing the Genetic Algorithms to get the desired response as an aid to the device related work The optimized parameters like phase angle, ac mobility, channel width, carrier concentration, lattice temperature and electron temperature will obviously save the search time for the technologists involved in the fabrication of devices

Keywords : Genetic algorithm, optimization, quantum wells, ac mobility, hot electron, probabilistic rules, carrier transport

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1. Introduction

There has been considerable interest in the study of the physical properties of the two-dimensional (2D) quantum wells [1-2]. Investigations on such two-dimensional (2D) quantum wells are already started and some of these devices are ready for commercial use in many applications [3-6]. Yet, there are many scopes for further investigation to improve the operations of such two-dimensional (2D) quantum structures [7-10]. In our work, we want to find out the optimized system parameters for the two-dimensional (2D) quantum wells for high frequency under hot electron condition. When a thin layer of lower bandgap semiconductor such as GaAs, is sandwiched between the layers of higher bandgap semiconductor such as (Al, Ga)As, then a quantum well (QW) is formed. In these structures, the two dimensional (2D) electronic transport parallel to the interfacial planes is allowed due to the layer thickness comparable to the de Broglie wavelength. Electron mobility in QWs is particularly high at low temperatures as modulation doping separates the electrons from their parent doner atoms reducing thereby the influence of ionized impurity scattering [6]. The main advantage of the quantum well (QW) over a single heterojunction is that the modulation doping on both sides of the quantum well is possible, so that higher electron concentrations are possible in quantum wells than the single heterojunctions [11-13]. The properties like electron mobility, Hall mobility, Hall to drift mobility ratio, *etc* are the main criteria for the study of two-dimensional (2D) quantum wells. Due to the dependence of these properties on the various system parameters, namely, the channel width, carrier concentration, lattice temperature, electron temperature, *etc*, the optimization of these system parameters of the two dimensional quantum wells (QWs) is very essential for suitable application in commercial market.

For the optimization, the various methods are already used, but due to some important advantages, genetic algorithm is used successfully in our work. It is a biological evolutionary process in intelligent search, machine learning and optimization problems and this algorithm is based on the mechanics of natural selection and natural genetics. In every generation, a new set of artificial creatures is created using bits and pieces of the fittest of the old; an occasional new part is tried for good measure. While randomized, genetic algorithms (GA) are no simple random walk. They efficiently exploit historical information to speculate on new search points with expected improved performance. The main theme of this algorithm is robustness. It is the balance

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between efficiency and efficiency necessary for survival in many different environments. GAs are theoretically and empirically proven to provide robust search in complex spaces. So GAs are now finding more widespread application in business, scientific and engineering circles. The reasons behind the growing numbers of applications are clear. These algorithms are computationally simple yet powerful in their search for improvement. In order for GA to surpass their more traditional in the quest for robustness, GAs must differ in some fundamental ways. (14) GA provides most canonical method than many search schemes.

In the present work, we intend to compute the optimized parameters using GA to get desired millimeter and sub millimeter wave response characteristics of GaAs quantum wells.

2. Method of approach

We consider square QWs of GaAs of infinite barrier height having channel width L_z For the 2D carrier concentration (n_{2D}), channel length (L_z), and the lattice temperature (T_L) used here, the separation between the lowest and the next higher subband is at least four times the average carrier energy. The electrons are, therefore, assumed to populate only the lowest subband of the square QWs in the infinite barrier height approximation. The carrier distribution is thus degenerate.

In the present work, we include the carrier scattering *via* deformation potential acoustic phonons, polar optic phonons, and ionized impurities. The effect of screening on the scattering rate for polar optic phonons is insignificant over the temperature range of interest [15] and hence not included in the present calculations. Screening is, however, incorporated for other scattering processes. Reduced ionized impurity scattering and improve carrier confinement establish a strong electron-electron interaction in the QW structure. This strong interaction in energy and momentum exchanges favours a heated drifted Fermi-Dirac distributión function for the carriers characterized by an electron temperature T_e and a drifted crystal momentum p_d. The establishment of an electron temperature is demonstrated by the photoluminescence experiment [16]. In presence of a heating electric field F applied parallel to the heterojunction interfaces, the carrier distribution in the QW is thus :

$$F(k) = f_0(E) + (\hbar p_d / m^*)\, k(f_0 / E) \cos\theta\,, \qquad (1)$$

where $f_0(E)$ is the Fermi-Dirac distribution function for the carriers, $\hbar$ is the Plank's constant divided by 2π, m^* is the electronic effective mass and θ is the angle between F and the $2D$ wave vector k of the carriers with energy E.

An ac electric field of amplitude F_1 and frequency ω superimposed on dc biasing field is applied. So the net field takes the form

$$F = F_0 + F_1 \sin\omega t\,.$$

Detailed mathematical calculation utilized in this article is available in Ref. (17). Electron temperature model is employed here together with energy and momentum balance equation for the carriers. Other relevant material parameters are used in the present calculations are represented in section 4. Empirical relations are established here in this work in the same way as done in Ref. (17).

In many optimization methods, we move gingerly from a single point in the decision space to the next using some transition rule to determine the next point. This point-to-point method is dangerous because it is a perfect prescription for locating false peaks in multimodal search spaces. By contrast, GAs work from a rich database of points simultaneously, climbing many peaks in parallel; thus, the probability of finding a false peak is reduced over methods that go point to point.

GAs require the natural parameter set of optimization problem to be coded as a finite-length string over some finite alphabet With GAs, the first step of our optimization process to code the parameter as a finite length string. There are many ways to code the parameter. At the moment, let's consider an optimization problem where the coding comes a bit more naturally.

A simple Genetic Algorithm is composed of three operators:- Reproduction, Crossover and Mutation.

Reproduction is a process in which individual strings are copied according to their objective function values. Copying strings according to their fitness values means that strings with a higher value have a higher probability of contributing one or more offspring in the next generation. This operator, of course, is an artificial version of natural selection, a Darwinian survival of the fittest among string creatures.

After reproduction, simple crossover may proceed in the following steps. First, members of newly reproduced strings in the mating pool are mated at random. Second, each pair of strings undergoes crossing over as follows.

An integer position t along the strings is selected uniformly at random between 1 and the string length less one [1, $P-1$] Two new strings are created by swapping all characters between positions ($t+1$) and P inclusively. For example, consider two strings X and Y.

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X= 10011 | 1011,

Y=00110 | 0010.

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Suppose in choosing a random number between 1 and 8 (9 – 1), as P = 9 as indicated in the above by dotted line. Then the result of cross over which produces two new strings indicated by X_1 and Y_1 (say).

X_1= 100110010,

Y_1=001101011.

The mutation operator plays a secondary role in the simple GA. We simply note that the frequency of mutation to obtain good results in empirical Genetic Algorithm studies is on the order of one mutation per thousand bit transfers. Mutation rates are simply small in natural population. Thus mutation is considered as a secondary mechanism of Genetic Algorithm adaption.

3. Method of optimization

Present work declares that a soft computing tool, GA is used to get the optimized system parameters of GaAs QW for a desired high frequency response characterized by a cutoff frequency (f_{3dB}). By the present work, a model of optimized system parameters of GaAs QW is obtained for a high frequency under hot electron condition. In GA, a fitness function is the main criteria for reproduction. The fitness values are used to favour high fitness individuals over low fitness individuals to take part in the process of reproduction. In the present application of GA, we find the f_{3dB} for a semiconductor quantum structure for its different system parameters. So we find the variation of f_{3dB} (cut off frequency at which the mobility falls to 0.707 of its low frequency value) and one particular parameter of the system where the other parameters are optimized by the Genetic Algorithm. By taking the other parameters in one form, we can be able to find the fitness values. These fitness values are converted to binary form and then proceed for further Genetic Algorithm operation.

4. Numerical results and discussion

In this optimization technique, we consider a square quantum well of GaAs and electron temperature model is employed for numerical calculations with the following system parameters : Electron effective mass $m^* = 0.61033\text{x}10^{-31}$ kg, longitudinal elastic constant, $C_l = 14.03\text{x}10^{10}$ N.m^{-2}, acoustic deformation potential, $E_l = 17.6\text{x}10^{-19}$ J, Static dielectric constant, $K_s = 12.52$, optic dielectric constant, $K_\infty = 10.82$, LO phonon angular frequency, $\omega_0 = 5.37\text{x}10^{13}$ rad s^{-1}, background ionized impurity concentration $n_{bi} = 6.0 \text{ x } 10^{21}$ m^{-3} longitudinal acoustic velocity $u_l = 5.22 \text{ x } 10^3$ms^{-1}. The frequency of the applied is varied and at each frequency the optimum parameters are determined by employing the Genetic algorithm for a particular dc biasing field. For a particular dc biasing field, it is possible to predict the

Table 1. Optimized parameters for dc bias field $F_0 = 1.0 \text{ x } 10^5$ v/m

Frequency GHz	Phase	Ac mobility μ_{ac} (m^2/v.s)	Carrier concentration n_{2D} (10^{15}m^{-2})	Channel width L_z (nm)	Lattice temperature T_l (K)	Electron temperature T_e (K)
10	6.76	5.06	9.0	120	77	327
20	13.68	4.54	10.0	120	100	318
50	30.01	4.43	9.0	120	87	305
100	49.24	3.60	10.0	120	110	302
200	56.94	1.88	8.0	105	150	240
250	67.19	1.68	9.0	100	150	268
300	68.74	1.37	8.0	85	200	290
400	66.70	0.99	8.0	120	250	322
500	63.18	0.75	5.0	100	300	336
600	67.16	0.65	5.0	100	300	336

Table 2. Optimized parameters for dc bias field $F_0 = 0.5 \times 10^5$ v/m

Frequency GHz	Phase	Ac mobility μ_{ac} (m^2/v.s)	Carrier concentration n_{2D} (10^{15}m^{-2})	Channel width L_z (nm)	Lattice temperature T_L (K)	Electron temperature T_e (K)
10	7.58	5.62	10.0	115	77	173
20	9.89	3.79	9.0	120	100	148
50	23.94	3.54	9.0	105	125	163
100	37.24	2.60	10.0	120	150	184
200	49.41	1.60	8.0	115	200	222
300	68.77	1.31	9.0	85	225	255
400	72.71	1.01	10.0	100	250	284
500	73.18	0.81	9.0	110	270	298
600	75.89	0.68	9.0	110	300	330
700	80.29	0.59	7.0	80	150	174

optimum values of the system parameters like electron temperature, channel width, carrier concentration, for the realization of a desired high frequency response and ac mobility. Optimized parameters have been computed by employing the Genetic Algorithms to get the desired high frequency response as an aid to the device related work. The optimized parameters will obviously save the search time for the technologists involved in the fabrication of the devices. The application of GA will enable the technologists involved in the fabrication to predict directly the system parameters for a device to be operated at a desired frequency with required ac mobility. The method of optimization studies how to describe and attain what is the best. Optimization theory encompasses the quantitative study of optima and methods for finding them. Optimization ensures performance toward some optimal point or points. There are several other optimization techniques, but they need auxiliary information for proper working. As for an example, gradient methods require derivatives in order to be able to climb to the current peak, and other local search procedures like the greedy methods of combinatorial optimization need access to most if not all. On the other hand, GAs have no requirements for all these auxiliary information. GAs are more canonical method than many schemes. Moreover, GA based techniques enable the technologists to determine the suitable optimized parameters directly to get the desired ac mobility and can be utilized during fabrication. From the Tables 1 and 2, it is revealed that for a frequency of 200GHz and for ac mobility of 1.88 m^2/v.s (Table 1) and 1.60 m^2/v.s (Table 2) the optimized system parameters are presented by the various columns of row 5 for both the tables. The optimized parameters for the biasing fields of 1.0 x 105 v/m and 0.5 x 105 v/m are represented in the tabular form in Table 1 and Table 2, respectively. This work has the potential of predicting the optimized system parameters, which will surely save the search time for the technologists involved in the fabrication of high frequency devices.

5. Conclusion

We have computed the optimized parameters using GA to get desired millimeter and sub-millimeter wave response characteristics. The application of GA in the device parameter optimization for getting the best performance is a new area of research. The optimized system parameters presented here, predict the better performance of GaAs QWs in the microwave and millimeter wave regime and can be used to analyse the experimental data when they appear in the literature. This is actually an application of a specialized soft computing tool and it is expected that the present model is capable of predicting the optimized parameters, which will surely save the search time for the technologists involved in the fabrication of high frequency devices.

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