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I-V characterization of a staircase quantum well infrared photodetector

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In this work, a quantum well infrared photodetector structure which consists of three different well thicknesses with three different barrier compositions producing a staircase-like conduction band profile with the reputation of 30 periods has been investigated. Dark current measurements have been done at the range from 6 K to 290 K temperature. Activation energies of the carriers have been obtained from the temperature dependence of the I-V measurements. The change of the activation energy with bias voltage has also been obtained. From the activation energy at zero bias and calculated quasi Fermi energy, barrier heights of the quantum wells and ground state energies were obtained. All obtained ground state energies have been found to be consistent with the results obtained from calculations with the transfer matrix method.

1 Introduction Quantum well infrared photodetectors (QWIP) sensing and imaging devices have developed over the past 15 years. QWIPs based on GaAs/AlGaAs structures have advantages such as they are based on well defined and matured epitaxial growth technology, can be designed and produced for multi wavelength detection and implemented in focal plane array imaging systems [1]. QWIPs with stepped or staircase barriers can operate at two or three wavelengths and have low dark currents. The main motivation of this study was to measure and investigate the dark current of a structure similar to the one which was theoretically proposed previously [2].

2 Experimental Structure of the devices investigated in this work depicted in Fig. 1. Three different well thicknesses with three different barrier compositions produces staircase-like conduction band profile as seen from Fig. 2. The doping concentrations of the wells are 5.0×10^{16} cm^{-3} and $Al_xGa_{1-x}As$ barriers are undoped. n+ GaAs, top and bottom contact layers are highly doped with Si at 1.0×10^{18} cm^{-3} concentration. High doping concentration and thickness of the contact layers prevents band bending and provides good ohmic contacts for the device [3]. All samples have cylindrical mesa geometry with ring contacts on the top. Samples which have A, B, C suffixes have 600 μm, D, E, F suffixes have 400 μm diameter.

1000 nm	n+ GaAs	1.0×10^{18} cm^{-3}	
50 nm	n GaAs	1.0×10^{18} cm^{-3}	
40 nm	i $Al_{0.21}Ga_{0.79}As$		
6.5 nm	n GaAs	5.0×10^{16} cm^{-3}	
40 nm	i $Al_{0.24}Ga_{0.76}As$		x30
5.5 nm	n GaAs	5.0×10^{16} cm^{-3}	
40 nm	i $Al_{0.3}Ga_{0.7}As$		
4.5 nm	n GaAs	5.0×10^{16} cm^{-3}	
40 nm	i $Al_{0.35}Ga_{0.63}As$		
1500 nm	n+ GaAs	1.0×10^{18} cm^{-3}	
	n+ GaAs Substrate	$1\text{-}2\times10^{18}$ cm^{-3}	

Figure 1 Staircase QWIP device structure.

Dark current measurements have been done with a dynamic gas exchange type continuous flow liquid He cryostat at the temperature range from 6 K to 290 K. Top contact of the device biased positively with respect to the bottom contact.

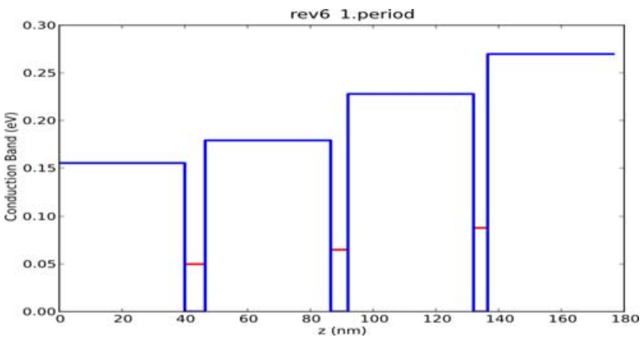

Figure 2 Conduction band structure and ground states of the device. Ground states have been calculated by the transfer matrix method.

3 Results Figure 3, shows I-V measurements taken between 6-110 K. Results which were taken between 6-70 K temperature range show that as the temperature decreases the threshold value of the current moves to higher voltages. This is a typical indication of the overwhelming tunnelling current over thermionic emission. As the temperature further increases from 70 K to 110 K, thermionic emission current becomes dominant over the tunnelling current and the dark current will be proportional to the concentration of the carriers which were activated by thermionic emission.

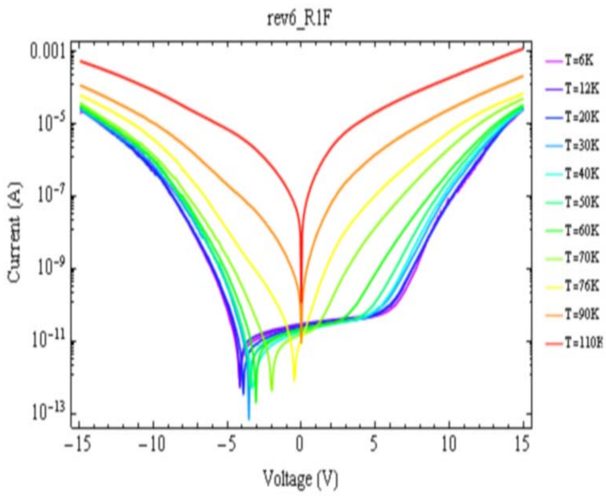

Figure 3 I-V curves of the staircase quantum well infrared photodetector at various temperatures.

As seen from Fig. 3, zero-bias offsets shift towards higher voltages as the temperature decreases.

4 Analyses and discussion In order to calculate the activation energy of the electrons in the quantum wells, temperature dependence of the dark current must be analysed. Ground state energies of three quantum wells can be obtained by an iteration technique with the help of the calculated barrier energies as explained in the below subsections.

4.1 Dark current in quantum well iInfrared photodetectors In quantum well infrared photodetectors tunnelling and thermionic emission are two main contributions to the dark current as depicted in Fig. 4.

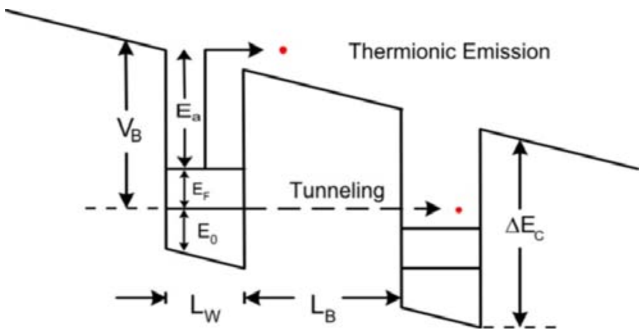

Figure 4 Current mechanisms and several energy values at the conduction band of a quantum well system [4].

Current due to the thermionic emission is proportional to the number of electrons having energies larger than the barrier height as in Eq. (1) [5-7].

$$n(T) = \frac{m^*}{\pi\hbar^2 L_w}\int_{E_0}^{\infty} f(E)T(E,V)dE \qquad (1)$$

where the first factor is the density of states in two dimensional systems divided by the quantum well width, L_w. *f(E)* is the Fermi-Dirac distribution given by

$$f(E) = (1+e^{(E-E_0-E_F)/k_BT})^{-1} \qquad (2)$$

where E_0 is the ground state energy, E_F is the two dimensional Fermi level which is measured relative to E_0, and $T(E,V)$ is the energy dependent tunnelling current transmission tunnelling transmission coefficient for a single barrier. Transmission coefficient can be set to zero for $E<E_b$ and one for $E>E_b$ under low bias conditions. Electrons which have more energies than the barrier height will satisfy $E\text{-}E_F>>k_BT$ condition and the Fermi-Dirac distribution can be approximated to Maxwell-Boltzmann distribution. Integration of the Eq. (1) under above assumptions will give the temperature dependence of the carrier density as in Eq. (3) where V_B is the barrier height [4].

$$n(T) = \frac{m^* k_B T}{\pi\hbar^2 L_w}\exp\left(-\frac{V_B - E_F}{k_B T}\right) \qquad (3)$$

Therefore dark current is proportional to barrier height as in Eq. (4)

$$\frac{I(T)}{T} \propto \exp\left(-\frac{V_B - E_F}{k_B T}\right) \qquad (4)$$

4.2 Quasi-Fermi level energy in two dimensional structures In a quantum well with n bound states density of electrons are given by Eq. (5) [8].

$$n^{2D} = \sum_{j=1}^{n} n_j^{2D} = \frac{m^* k_B T}{\pi\hbar^2} \sum_{j=1}^{n} \ln(1 + e^{(E_F - E_j)/k_B T}) \quad (5)$$

here, E_j is the energy of the j[th] bound state and m^* is the effective mass of the electrons in the quantum well. If there is one state in the quantum well, quasi Fermi energy can be written as

$$E_F = E_0 + k_B T \ln\left(e^{\frac{n^{2D}\pi\hbar^2}{m^* k_B T}} - 1 \right) \quad (6)$$

where E_0 is the ground state energy of the quantum well. Note that here E_F is not the Fermi energy of the total structure, instead it is a quasi Fermi energy which gives the carrier population within a bound state [9]. This equation can be investigated in two different limits. At $n^{2D}\pi\hbar^2 << m^* k_B T$ limit, quasi Fermi energy can be approximated as

$$E_F \approx E_0 + k_B T \ln\left(\frac{n^{2D}\pi\hbar^2}{m^* k_B T} \right) \quad (7)$$

and at $n^{2D}\pi\hbar^2 >> m^* k_B T$ limit,

$$E_F \approx E_0 + \frac{\pi\hbar^2 n^{2D}}{m^*} = E_0 + \frac{\pi\hbar^2 n^{3D} L_w}{m^*} \quad (8)$$

here n^{2D}, n^{3D} are two and three dimensional carrier densities respectively. At this limit, quasi Fermi energy can be approximated as independent from the temperature. Investigated samples do not include superlattices due to wide barrier thicknesses and only the wells are doped. In this case instead of sum of barrier and well thicknesses only the well width can be used in Eq. (8).

4.3 Dark current analyses The temperature dependence of the dark current has been investigated at various bias voltages, taken from Fig. 3 and plotted in Fig. 5. From the slope of $\ln(I(T)/T)$ versus $1000/T$ data, the activation energy which is V_B-E_F can be calculated.

Since the thermionic emission is not dominant mechanism below 60 K the results were excluded in the calculations. Bias voltage dependence of the activation energy is plotted in Fig. 6. The activation energy at zero bias has been found by extrapolating the data taken between 4 to 9 V forward bias voltages. This selected range is the linear portion of the entire bias range. Finally barrier height relative to the ground state at zero bias was found by adding quasi Fermi energy to activation energy at zero bias.

These energies are depicted in Fig. 4. ΔE_C conduction band discontinuities and E_0 ground state energies of three quantum wells have been calculated by an iteration technique utilizing Eqs. (9), (10) and (11) [4].

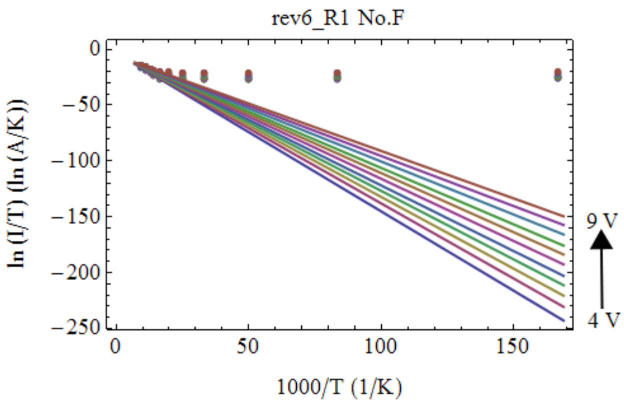

Figure 5 Temperature dependence of the dark current at several bias voltages.

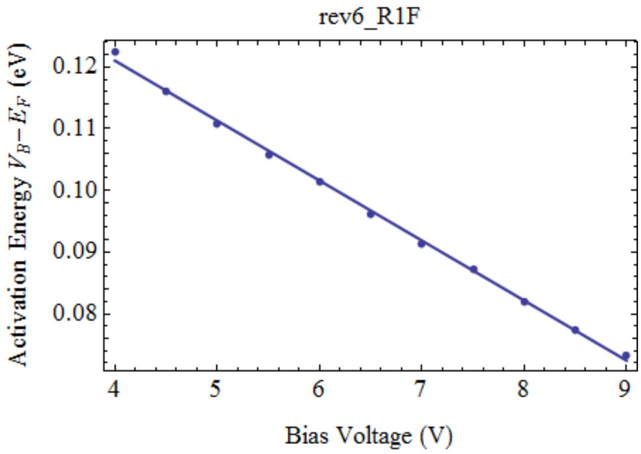

Figure 6 Change in the activation energy with bias voltage.

$$\Delta E_C = E_a + E_F + E_0 = V_B + E_0 \quad (9)$$

$$\Delta E_C^{\max} = V_B + E_0^{\max} = V_B + \frac{\hbar^2\pi^2}{2m_w^* L_w^2} \quad (10)$$

Table 1 *ΔEc* and ground state energies of the three quantum wells.

Sample Code	Selected Temperatures (K)	Activation Energy E_a (meV)	Corresponding Wavelength (nm)	Ground States	Ground State Energy (meV)		Conduction Band Discontinuity ΔE_c (meV)
					Transfer Matrix	Iteration	
rev6_R1B	76, 90, 110	135	9185	1. Well E_{11}	50	53	189
				2. Well E_{21}	65	65	201
				3. Well E_{31}	88	83	219
rev6_R1C	76, 90, 110	133	9323	1. Well E_{11}	50	53	187
				2. Well E_{21}	65	65	199
				3. Well E_{31}	88	83	217
rev6_R1D	70, 76, 90, 110	147	8435	1. Well E_{11}	50	54	202
				2. Well E_{21}	65	67	215
				3. Well E_{31}	88	86	234
rev6_R1F	70, 76, 90, 110	162	7654	1. Well E_{11}	50	56	219
				2. Well E_{21}	65	69	232
				3. Well E_{31}	88	89	252

$$\sqrt{\frac{E}{m_w^*}}\tan\left(\sqrt{\frac{m_w^* L_w^2 E}{2\hbar^2}}\right)=\sqrt{\frac{\Delta E_C - E}{m_b^*}} \tag{11}$$

In the iteration process an infinite quantum well to the finite quantum well approach has been used, which the barrier height ΔE_C is converged to the corresponding value of ground state. The ground state energy of an infinite quantum well is given by $\hbar^2\pi^2/2m^*_w L^2_w$ as in the Eq. (10). Then the ground state energy of the finite quantum well can be calculated by solving Eq. (11) numerically [10, 11]. Here the finite barriers were assumed to be symmetrical and the quasi Fermi energy of the quantum wells assumed to be independent of temperature.

In the symmetrical barrier assumption, the average values of effective masses in the consecutive barriers are taken due to staircase like barrier structures. Iteration has been done by pursuing the following step; first V_B barrier height and E_0^{max} and ΔE_C^{max} were calculated. ΔE_C^{max} value is used in the first iteration then a new E is obtained by solving Eq. (11). Barrier height is added to the E value and a new ΔE_C value is obtained for the next iteration of Eq. (11). In Table 1, all the results were summarized. Since the iteration technique is semi-empirical, the obtained results are in good agreement with the calculations done by the transfer matrix method.

5 Summary Temperature and bias voltage dependent dark current measurements and analyses of a staircase QWIP have been done. The measured dark currents were low as theoretically proposed for similar staircase QWIPs [2, 3]. Bias dependent activation energies were found from I-V measurements. Ground state, barrier height energies were obtained by the infinite to finite quantum well iteration technique. All obtained results were consistent with the conduction band structure of the device calculated by the transfer matrix method. It is also found that asymmetric barriers of the structure can be thought as averaged symmetric barriers under a specific bias range.

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