Design and Simulation of QW-ASPAT Diode with Different Barrier Dimensions

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Abstract*—This study aims to analyze and simulate the effect of varying Barrier Thickness (tb) on the performance of an $Al_xGa_{1-x}As/AlAs$ Quantum Well Asymmetric Spacer Tunnel Diode (QW-ASPAT). Based on solution of Schrödinger equation, the current flowing through the quantum tunnel is directly affected by changes in barrier thickness. Increasing the barrier thickness (tb) significantly reduces the current density through the tunnel and increases the junction resistance from 9.4MΩ when tb=2nm to 654MΩ when tb=5nm. As a result, the device's ability to detect low-power signals decreases with increasing barrier thickness. However, changing the barrier thickness has a minimal effect on the curvature coefficient. Furthermore, this study aims to analyze and simulate the effect of changing the barrier height on the performance of QW-ASPAT using $Al_xGa_{1-x}As$ lattice as the barrier with different Al concentration. Increasing the barrier height by increasing Al concentration significantly reduces the tunnel current and increases the junction resistance. Nevertheless, the effect of changing the barrier height on the curvature coefficient is slightly shallow. The simulation in this study relies on the SILVACO environment in order to understand the characteristics of the QW-ASPAT diode, in addition to the ADS environment analyze the behavior of the RF detector diode in the receiver circuit when the barrier coordinates are changed.

Keywords— Barrier, Asymmetric layers, QW-ASPAT, Curvature coefficient, Junction resistance.

I. INTRODUCTION

The emergence of communication systems with high data transfer rates is an absolute necessity with spread of global intelligent systems[1][2][3]. This purpose prompted to emergence of high-speed devices in the last century [4]. As result, the Schottky Barrier Diode (SBD) considered one of the most widely used in high-speed communication systems[5]. However, the emergence of devices such as the Asymmetric Spacer Layer Tunnel Diode (ASPAT) and Resonant Tunnel Diode (RTD) diode based on the quantum tunneling phenomenon has gain more attention at the end of the last century [6]. ASPAT distinguished by low temperature sensitivity comparing to Schottky diode [7]. Furthermore, ASPAT is a zero bias detector, which making it suitable for low-power communication systems. Consequently, ASPAT diode considered very suitable for RF detection at high frequencies as well as low power sources [8].

The basic structure of the ASPAT consists of a layered array of III-V elements from the periodic table (in this study).Since the ASPAT diode relies on the quantum tunneling phenomenon, the most critical layer in the structure is the barrier. The barrier is surrounded by two unequal layers with thickness ratio equal to 40:1. The performance of the ASPAT depends on the properties of these critical layers.

This study presents will analyise the effect of barrier coordinates on the ASPAT performance. Because ASPAT relies on quantum tunneling, the barrier has a significant effect on the number of transmitted charge carriers through the tunnel. According to the solution of the one-direction Schrödinger equation, increasing the barrier thickness leads to a decrease in the tunnel current [6].Furthermore, the junction resistance of this device decreases with decreasing barrier thickness. Similar to changing barrier thickness, the probability of charge carrier transport in the tunnel can be influenced by changing the tunnel height according to the Schrödinger equation. Increasing barrier height reduces the probability of electrons passing through the tunnel, and vice versa. Although increasing the barrier height reduces the effect of thermonic emission [9], the price is a reduction in the current flowing through the device. Curvature Coefficient (Kv) is the most important characteristic of detector diode, based on relationship of sensitivity [7]. Kv can be obtained from the I-V curve of the diode. When, $K_v = (\partial^2 i/\partial V^2)/(\partial i/\partial V)$, the value of Kv depends on the asymmetry between the forward and reverse currents of the diode. Kv = 40V-1 for a Schottky diode and Kv = 70V-1 for a germanium diode [10],[11].The study[8] present the design of QW-ASPAT that give Kv more than 30V-1 by exploiting the presence of a thin layer of quantum well on the long spacer side.

The main simulation of $Al_xGa_{1-x}As/AlAs$ QW-ASPAT diode was performed using the SILVACO environment. The simulation aims to analyze the effect of varying the barrier thickness and barrier height on the DC and RF characteristics. To achieve wide look and understanding the diode behaviors, the ADS environment is used to analyze the RF characteristics of the detector.

II. QW-ASPAT STRUCTURE

The epitaxial layer used in this study to understand the effect of barrier thickness shown in Fig. 1 [6]. Typically, the AlAs is an indirect tunnel with an energy gap of 2.1 eV. To achieve a direct tunnel, the AlAs layer thickness is assumed to be less than 5nm [12]. As for the other layers, shown in Fig. 1, the mesa size of diode used in this study is 4×4 μm² in order to obtain the small size for diode structure. On the other hand, $Al_xGa_{1-x}As$ can be used instead of AlAs to modify the barrier layer. Increasing the Al concentration leads to a change in barrier height, while the other layers in the QW-ASPAT structure remain unchanged. Consequently, the effect of

varying the barrier height on the device can physically investigated.

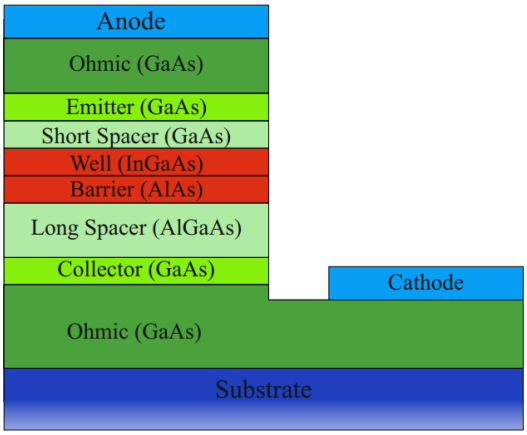

Fig. 1 Epitaxial layer of AlxGa1-xAs/AlAs for understanding the effect of changing barrier thickness

III. THE PARAMETERS OF PROPOSED QW-ASPAT

According to the solution of the Schrödinger equation, the thickness of the barrier has a fundamental effect on the probability of electrons passing through the tunnel. The probability of electrons appearing on the opposite side of the tunnel decreases as the barrier thickness increases. This is due to the wave motion of electrons. In addition to the decrease in tunneling current, the junction resistance (Rj) increases with increasing barrier thickness. Increasing the junction resistance value has a significant effect on the size of the matching circuit in the receiving antenna system.

In fact, in forward bias, the barrier height is lower than in reverse bias. Electrons then accumulate in the QW layer, causing an increasing in energy of accumulated electrons and making it easier to cross the barrier. However, in reverse bias, the electrons falling into the QW layer which have no enough energy levels to escape from the well, causing a decrease in the reverse current. Furthermore, a long spacer causes a voltage drop when reverse bias is applied. For this reason, a QW layer is added to increase the asymmetry between the diode's forward and reverse currents [8]. This structure increases the Kv value, increasing the diode's sensitivity, with respect to Eq. 1 [7]:

$$\beta_v = 2Z_o K_v \tag{1}$$

When, βv denoting the diode sensitivity and Zo is the source (antenna) impedance, and for simulation purpose, the SILVACO environment applied, by using the DeckBuild tool. To provide the electrical properties, ASPAT diode represented as a 2-D sections. Furthermore, the physical properties (such as current or capacitance) calculated using a pointed grid called a mesh. To represent the device in 3D, the results of the two-dimensional real representation combined to obtain the results of overall configuration (such as the total current or the total resistance). Semiconductor Isolated Semiconductor (SIS) model used to obtain the solution of the 1-D Schrödinger equation through the tunnel as illustrated in Eq. 2 :

$$P_T = \frac{16(H_b - E)}{{H_b}^2} e^{-2W\frac{\sqrt[2]{2m^*(E-H_b)}}{\hbar}} \tag{2}$$

Where PT represent tunneling probability, E is the electron energy, m* is effective mass, $\hbar$ is (h/2π) when h is balnk's constant, Hb and W represent height and thickness of the barrier respectively. The barrier thickness was varied in this study to understand the effect on the DC and RF characteristics of the diode at 300 K. Note that the barrier thickness does not exceed 5 nm to achieve direct tunnel transmission [12].

IV. RESULTS AND DISCUSSIONS

A. *Physical Parameters of QW-ASPAT Simulation with SILVACO*

1) *For Variable Barrier Thickness*: Fig. 2 shows the I-V curve of the diode according to parameters in Table 1, with varying barrier thickness. As a result, the tunnel current decreases with increasing barrier thickness. According to the Schrödinger equation, the probability of charge carriers passing through the tunnel decreases with increasing barrier thickness.

Table 1 Parameters of $Al_xGa_{1-x}As$/AlAs used in this study with different barrier thickness

Layer	Thickness(nm)	doping(cm^{-3})
GaAs (Ohmic)	300	4×10^{18}
GaAs (Emitter)	50	1×10^{17}
GaAs (Spacer1)	5	1×10^{14}
$In_{0.18}Ga_{0.82}As$(QW)	6	1×10^{14}
AlAs(Barrier)	Varied	1×10^{14}
$Al_xGa_{1-x}As$(Spacer2)	200	1×10^{14}
GaAs (Collector)	50	1×10^{17}
GaAs (Ohmic)	450	4×10^{18}

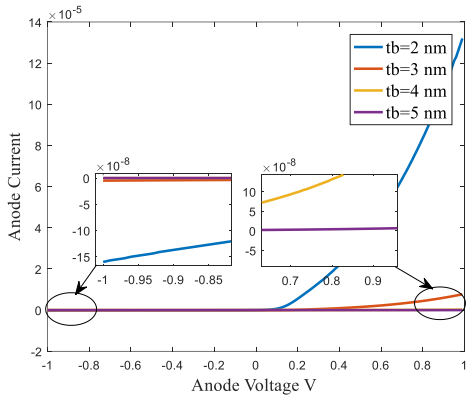

Fig. 2 I-V curve for $Al_xGa_{1-x}As$/AlAs with different barrier thickness

On the other hand, the effect of changing the barrier thickness is dominant on the junction resistance (Rj) value according to the relationship ($R_j = \partial V / \partial i$) as shown in Fig. 3. Rj increases significantly as the barrier thickness increases, thus achieving the current-resistance relationship. As a result, changing the value of Rj places an additional burden on the matching circuit at the receiver.

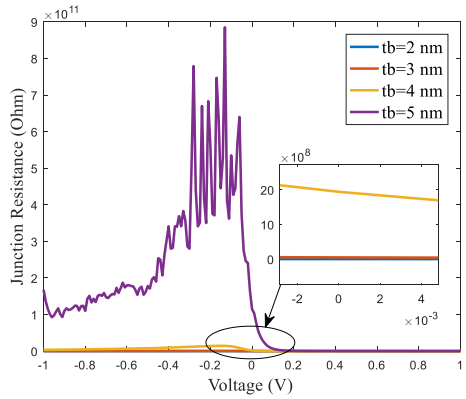

Fig. 3 Junction resistance for different barrier thickness in SILVACO environment

Fig. 4 shows the change in Kv curve when the barrier thickness is changed using the SILVACO environment. $\partial V/\partial i$ is unaffected by changing the barrier thickness because obstructions that impede the forward current will also impede the reverse current. Due to the asymmetric design of the ASPAT, the greatest asymmetry between the forward and reverse currents occurs at zero bias.

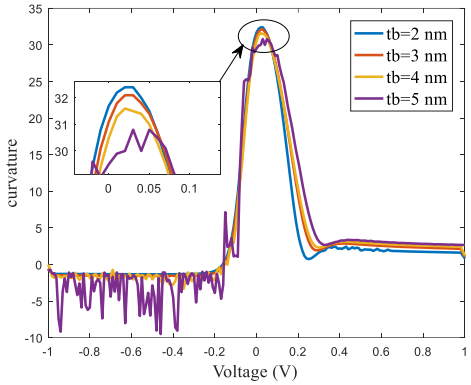

Fig. 4 Curvature coefficient for different barrier thickness

2) Variable Barrier Height: To study the behavior of an ASPAT diode when the barrier height is changed, a barrier with the ability to change its height must applied. For this purpose, AlxGa1-xAs used as barrier. Fig. 5 shows the band diagram for this design illustrating varying barrier height according to Table 2.

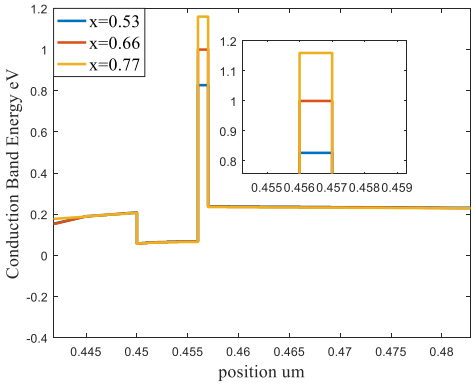

Fig. 5 Conduction band diagram of $Al_xGa_{1-x}As$ with different barrier height

Table 2 Parameters of QW-ASPAT $Al_xGa_{1-x}As$ used in this study with different barrier height

Layer	Thickness(nm)	doping(cm^{-3})
GaAs (Ohmic)	300	4×10^{18}
GaAs (Emitter)	50	1×10^{17}
GaAs (Spacer1)	5	1×10^{14}
$In_{0.18}Ga_{0.82}As$(QW)	6	1×10^{14}
$Al_xGa_{1-x}As$ (Barrier)	1.5	1×10^{14}
$Al_xGa_{1-x}As$(Spacer2)	200	1×10^{14}
GaAs (Collector)	50	1×10^{17}
GaAs (Ohmic)	450	4×10^{18}

The primary purpose of using $Al_xGa_{1-x}As$ as barrier is to obtain a material with a variable energy gap. The energy bandgap for $Al_xGa_{1-x}As$ changes when the concentration of Al in lattice changed, which is denoted by the symbol x. Depending on the heterojunction characteristic, the discontinuity can increase when the properties of the material (energy bandgap and electron affinity) change. Based on that, this change in material properties provides greater freedom in choosing the barrier height. For this reason, $Al_xGa_{1-x}As$ was used in this study as a barrier to understand the behavior of varying barrier height on ASPAT performance. In fact, the highest Al concentration value is x = 0.4 to maintain working with direct tunneling. On the other hand, if operating at x > 0.4 indirect tunneling dominate. For this reason, the barrier thickness reduced to achieve direct tunneling, as in the AlAs case [12].

As with barrier thickness case, changing the barrier height affects the probability of electrons moving through the tunnel. According to the Schrödinger equation, increasing the barrier height lead to reduce the number of electrons moving through the tunnel. Conversely, decreasing the barrier height increases the probability of electrons passing through the tunnel. Barrier height has an additional effect on ASPAT performance. Where the thermonic emission is affected by the height of the barrier as in [6].

The number of excited charge carriers moving over the barrier decreases as the temperature changes. However, the probability of electrons tunneling decreases, according to Schrödinger's principle.

Fig. 6 illustrates the behavior of the I-V curve for an ASPAT diode at different barrier heights. The barrier height changes with varying Al concentration ratios in the $Al_xGa_{1-x}As$ structure. In this study, the Al concentration ratios at the barrier are x = 0.53, 0.66, and 0.77, with the highest barrier height occurring at x = 0.77 and the lowest at x = 0.53. The variation in I-V curve values is due to the different barrier heights, as shown in the Fig. 5. As the height of the barrier decreases, the amount of current flowing through it increases, according to the Schrödinger equation. Therefore, the current flowing through the tunnel when x = 0.53 is greater than the current flowing when x = 0.77 at the same barrier thickness.

On the other hand, unlike the relationship between current and barrier height, Rj increases with increasing barrier height, thus exhibiting a relationship between current and resistance. Although the change in Rj's value with varying barrier height is not as large as the change in Rj's value with varying barrier thickness, this difference is still noticeable, as shown in Fig. 7.

Although the I-V curve varies with changing the barrier height, this change occurs almost equally in the forward and reverse currents. Consequently, the value of Kv is almost

stable (with a slight change) while changing the barrier height, as shown in Fig. 8.

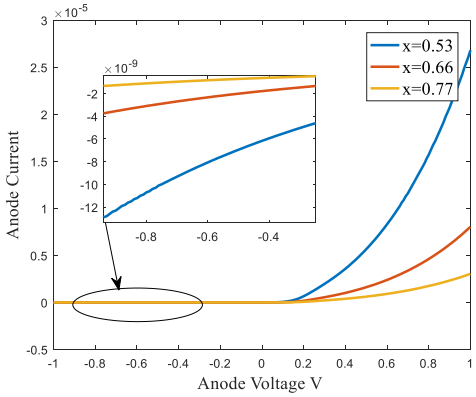

Fig. 6 I-V curve for $Al_xGa_{1-x}As$ with different barrier height

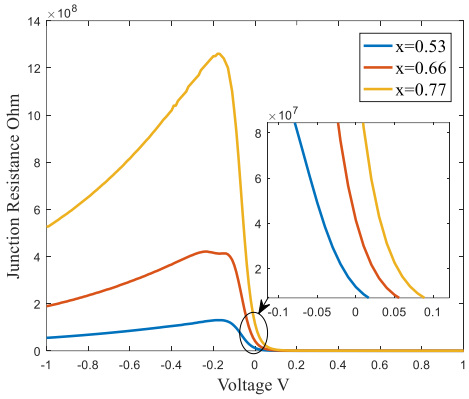

Fig. 7 Junction resistance of $Al_xGa_{1-x}As$ with different barrier height

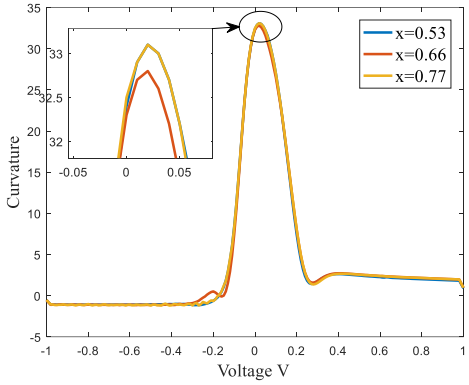

Fig. 8 Curvature coefficient of $Al_xGa_{1-x}As$ with variable barrier height

B. *QW-ASPAT as RF Detector with ADS environment*

To better understand the behavior of an ASPAT diode as an RF detector when the barrier dimensions change, the ADS environment is used to represent the equivalent circuit of the ASPAT in a receiver circuit [3]. For this reason, the SDD block in the ADS program used to represent ASPAT as a set of equations. Fig. 9 illustrates the equivalent representation of the receiver circuit, which consists of the source (Zs), the matching circuit (SmithChart), the equivalent ASPAT circuit, and the load circuit representing the low-pass filter.

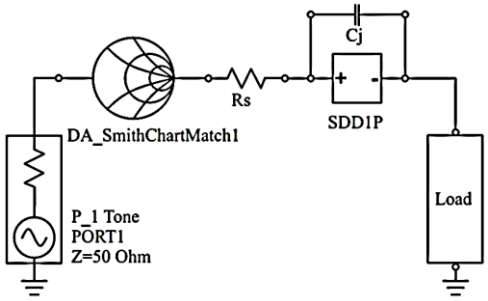

Fig. 9 Equivalent circuit of RF detector circuit

The receiver operates at -20 dBm and operating frequency of 100 GHz, with the matching circuit tuned to this frequency. One of the most important performance criteria for an RF detector is the sensitivity. In fact, sensitivity depends heavily on the Kv value and the specifications of the synchronization circuit and the antenna, according to Equation (1). For this reason, the sensitivity variation is small when changing the barrier thickness, as shown in Fig. 10. Similarly, changing the height of the barrier does not have a significant effect on the sensitivity of the diode because the Kv difference is slightly small, as shown in Fig. 11.

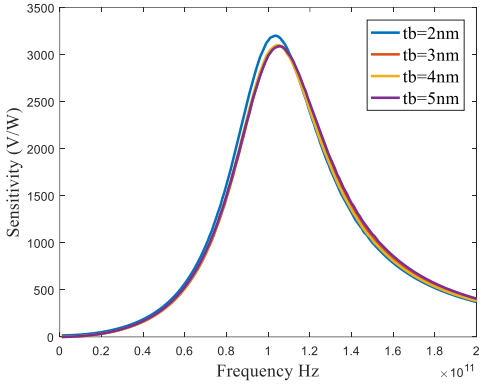

Fig. 10 Sensitivity of $Al_xGa_{1-x}As$ RF detector with different barrier thickness

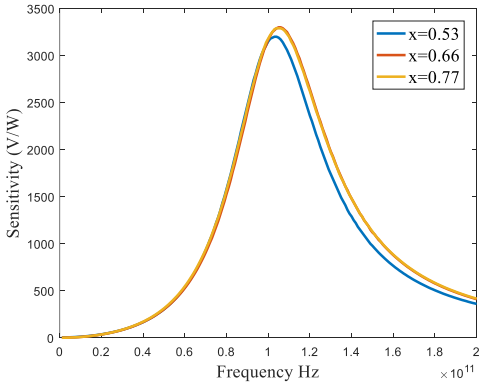

Fig. 11 Sensitivity of $Al_xGa_{1-x}As$ RF detector with different barrier height

On the other hand, the output voltage curve of the diode is used to understand the behavior of the RF detector when the input power is changed from and the frequency is held constant at 100 GHz. Fig. 12 illustrates the relationship

between the output voltage and input power as the barrier thickness changes. When the barrier thickness increases, the output voltage of the diode decreases due to the higher Rj value. Similarly, changing the barrier height affects the output voltage of the diode, as shown in Fig. 13. Increasing the barrier height leads to an increase in the Rj value. Consequently, the voltage drop across the diode increases, resulting a decrease in the output voltage. For this reason, the lower the value of Rj, the more the diode is able to detect the input power, even if it is small, compared to a diode with a high junction resistance.

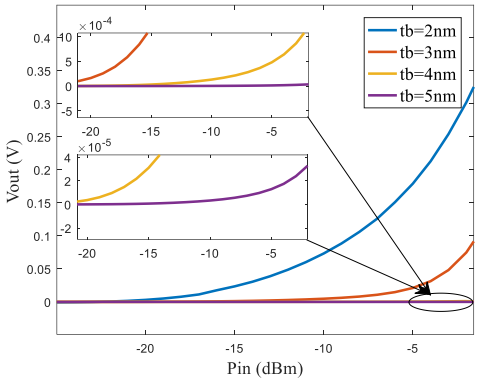

Fig. 12 Relationship of input power and output voltage for $Al_xGa_{1-x}As$ RF detector with different barrier thickness

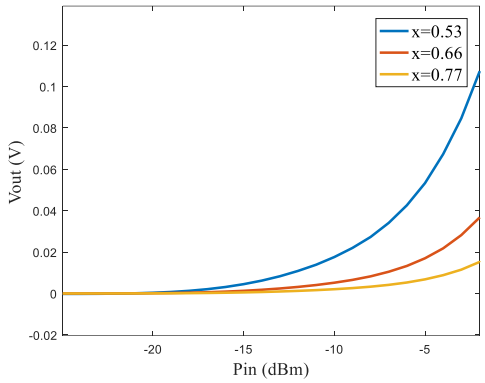

Fig. 13 Relationship of input power and output voltage for $Al_xGa_{1-x}As$ RF detector with different barrier height

CONCLUSION

The barrier coordinates have a significant impact on the performance of an RF detector. The current flowing through the quantum tunnel depends on the barrier coordinates. Increasing the barrier thickness causes a decrease in the tunnel current with obvious increases in junction resistance. Increasing the barrier thickness reduces the diode's ability to detect low-power signals and the sensitivity of the RF detector is not significantly affected by changing the barrier thickness. Similarly, increasing the barrier height reduces the tunnel current and increases the junction resistance, but the curvature coefficient changes only slightly. Consequently, the RF detector's ability to detect low-power signals is reduced. Moreover, the sensitivity of the RF detector is not significantly affected by changes in barrier height; the curvature coefficient does not change noticeably.

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