Design and Simulation of Double Quantum Well AlxGa1-xAs/AlAs ASPAT Diode

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***Abstract*— Based on the development of communication systems and the need for devices with low power and high speed. This study involved the design and simulation of AlxGa1-xAs/AlAs Asymmetrical Spacer Tunnel (ASPAT) diode for radio signals detection. Two different ASPAT architectures were employed with difference in the number of quantum well (QW) layers. AlxGa1-xAs used in the long space layer with Several Al concentrations were analyzed. The detectors demonstrated that increasing the Al concentration in the long space layer increases the curvature coefficient, leading to increased sensitivity. The study also showed that adding a second QW layer associated with the long space layer enhances the detector's ability to detect low-power signals. SILVACO ATLAS software was used to obtain the physical properties of the different models. On other hand, the ADS environment was used to simulate the various ASPAT architectures and their capabilities to detecting the RF signals within communication systems.**

Keywords— ASPAT, quantum well, AlxGa1-xAs, junction resistance, curvature coefficient.

Introduction

Modern wireless communication systems focused on dealing with signals with high frequency and low power applications such as medical applications are undergoing a massive leap driven by the requirements of fast data transmission systems [1]. As result, RF detectors play a pivotal role, relying on the nonlinear characteristics of the current-voltage relationship of semiconductors devices to convert received signals into DC voltages. For decades, Schottky barrier diodes (SBDs) have been the dominant choice in this field [2]. However, Schottky diodes face fundamental challenges that limit their efficiency in modern applications. They are considered highly affected by thermal changes. On other hand, sometimes require an external bias voltage, which make lead to some complex theoretical constraints that impose a ceiling on the curvature coefficient (Kv) of no more than 40 V^{-1} when operating at zero bias [3].

As result, Asymmetric Spacer Layer Tunnel Diodes (ASPAT) have emerged, which were developed to overcome the shortcomings of Schottky [4]. By introducing interested thermal stability and ability to operate with high efficiency at zero bias voltage makes ASPAT become suitable choice for RF detector [5].

Despite the interested thermal stability and physical characteristics of conventional ASPAT diode, bt curvature coefficient still relatively low comparing with SBDs. As result, conventional ASPAT diode detector suffer from low sensitivity performance which affected by curvature coefficient. To overcom this impairment, researchers turned to incorporating a single quantum well (QW) layer into the short spacer layer of the diode [2]. This adding lead to raises the effective energy barrier (such as the AlAs barrier in this study) at the reverse biasing state. As result, this additional layer causes reducing in the leakage currents. In addition, this structural modification lead to enhancement in the curvature coefficient by increased from approximately 33 V^{-1} to 35 V^{-1}, which approaching the Schottky theoretical limit. On the other hand, the junction capacitance decreased, which contributing to an increase in cut off frequency for the detector [6].

Despite the notable success of single quantum well ASPAT (SQW-ASPAT) in improving the curvature coefficient and reducing junction capacitance (Cj), RF detectors designed based on them still face a critical challenge relate to high junction resistance (Rj) at zero bias. This high resistance makes designing a matching network between antennas and detector circuit is very difficult. In addition, increasing the Rj value causes reducing the sensitivity of the detector at very low power levels.

This scientific and practical problem need to explore an advanced architecture based on inserting another QW layer incorporate with long spacer layer the Double Quantum Well ASPAT (DQW-ASPAT) Diode. The Double Quantum Well architecture allows for more precise achieve of quantum tunneling mechanism, with keeping the ability of nonlinear properties of ASPAT.

This study based on a detailed simulation and analytical study depending on SILVACO an ADS environments of two advanced structural designs for ASPAT diodes. The first one is an eight layer SQW-ASPAT, and the second one is an improved double quantum well diode (DQW-ASPAT). The methodology aims to examine the physical characteristics at zero bias detector in order to demonstrate the effect of the double well structure in reducing the junction resistance and enhancing the sensitivity of the circuit of RF detector.

I. METHODOLOGY AND RESULTS

The structure of both ASPAT devices is built with a standard 4x4 mesa size within the SILVACO ATLAS software coordinate system to obtain the physical parameters. The SIS model used for calculating the probability of electrons passing through the tunnel. This Model provide a precise calculation of the band discontinuity.

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A. *Singl Quantum Well ASPAT*

The AlxGa1-xAs/AlAs SQW-ASPAT design is eight-layer precisely arranged from top to bottom as shown in Fig1. TABLE 1 shows the characteristics of the SQW-ASPAT design layers. The top and bottom metallic layers are designed to form a low resistance ohmic contact. The emitter and collector are heavy doped GaAs layers to provide a stable injection current of electrons. Short Spacer layer with thickness 5nm presented with lightly doped GaAs where the confinement process begins. Quantum well assumed a thin and low doped layer with In0.18Ga0.82As. The concentration of Indium responsible for deepening the well and lowers the bottom of the conduction band at the well layer to enhance quantum confinement. A thin, low-doping AlAs layer primarily responsible for creating a high energy barrier that governs the quantum tunneling mechanism. The thickness of the barrier in this study is 5nm in order to ensure the direct tunneling achieved [7],. On the other side, the long spacer layer have 200nm thickness (40:1 to short spacer) with low doping AlxGa1-xAs with different Al composition. Asymmetric feature of this device relative to asymmetry between short and long spacer layers that gives the diode its asymmetrical behavior at zero bias [8].

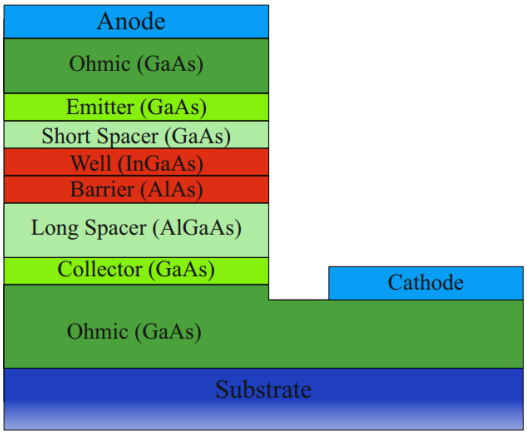

Fig1 The epitaxial layer for AlxGa1-xAs/AlAs SQW-ASPAT

TABLE 1 The characteristics of SQW-ASPAT layers

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)	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 electrical and physical parameters of SQW-ASPAT obtained by DeckBuild software of SILVACO ATLAS environment. The SIS model applied to find the solution of Schrödinger equation which govern the tunnel mechanism :

$$P_T = \frac{16(H_b - E)}{{H_b}^2} e^{-2W\frac{\sqrt[2]{2m^*(E-H_b)}}{\hbar}} \quad (1)$$

when PT is the probability of tunneling, E& m* represent electron energy and effective mass respectively, $\hbar$ is (h/2π) when h is balnk's constant, Hb and W represent height and thickness of the barrier respectively.

Fig 2 illustrates the conduction band for SQW-ASPAT design at different Al concentrations. Increasing the Al concentration in the long space increases the asymmetry between the forward and reverse currents by altering the conduction band's discontinuity with the barrier. The non-linear behavior of the I-V curve at different Al concentrations in the long space with SQW-ASPAT can be observed in Fig 3. One of the advantages of adding a QW layer is the increased discontinuity of the conduction band at this layer. This behavior lead to increases the height of the energy barrier and reduces thermal leakage current. On other hand increasing the Al concentration causing clear decrease in the tunneling current.

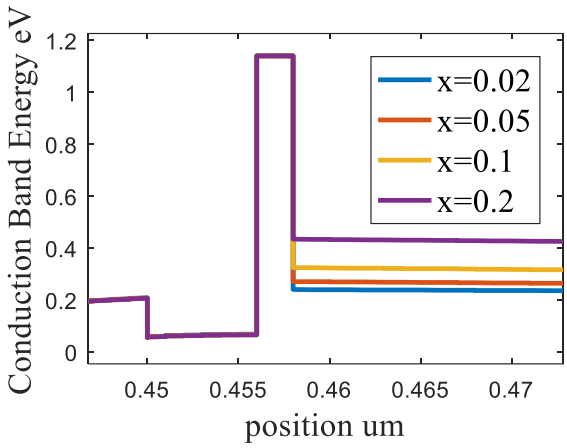

Fig 2 Conduction band diagram for SQW-ASPAT with different Al concentrations.

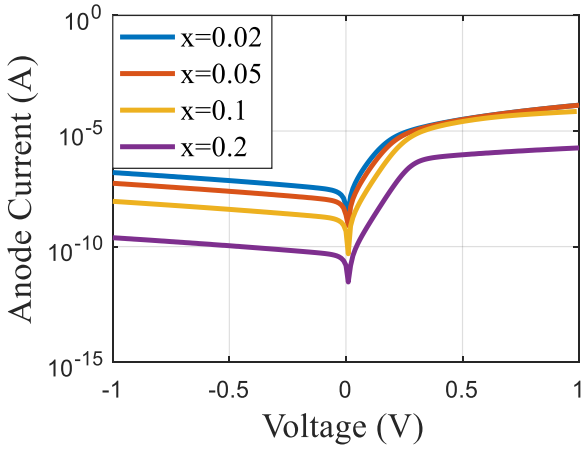

Fig 3 I-V curve for SQW-ASPAT with different Al concentrations.

The curvature coefficient represents a measure of the nonlinearity of the device. It depends on the result of dividing the second derivative by the first derivative of the current($K_v = (\partial^2 i/\partial V^2)/(\partial i/\partial V)$). The Kv value mainly relays on asymmitry between the forward and revers current. Since the presence of a QW layer increases the difference

between forward and reverse currents by trapping electrons during reverse bias within the well. As a result, the presence of a QW layer increases the Kv value. On the other hand, increasing the Al concentration in the long space layer lead to increases the obstacles to reverse current, thus increasing current asymmetry and consequently increasing the Kv value as shown in Fig 4.

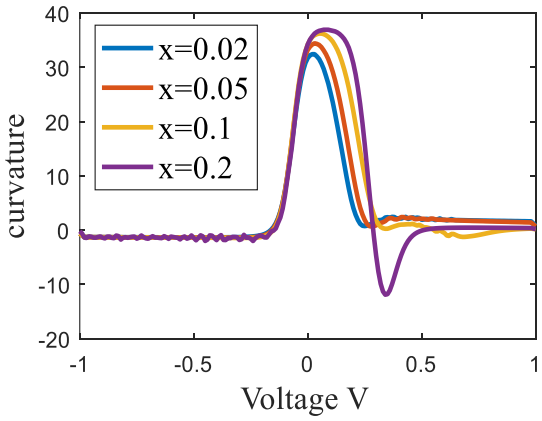

Fig 4 Curvature coefficient for SQW-ASPAT with different Al concentrations.

The junction resistance represents the inverse of the first derivative of the current at zero bias. Increasing the Al concentration in the long space reduces the tunnel current at zero bias, thus decreasing the value of the inverse of the first derivative of the tunnel current and consequently significantly increasing the value of Rj as shown in Fig 5.

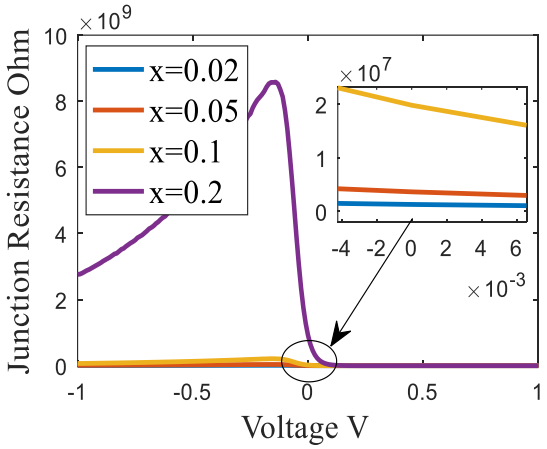

Fig 5 Junction resistance of AlxGa1-xAS/AlAs for SQW-ASPAT with different Al concentrations.

Since the model used in this study is SIS in the Silvaco Atlas software, changing the aluminum concentration in the long space has a minimal effect on the Cj value. The Al concentration, in fact, reduces the Cj value, as shown in Fig 6.

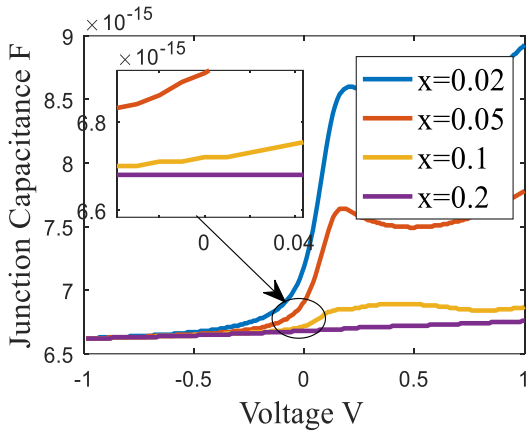

Fig 6 Junction capacitance of AlxGa1-xAS/AlAs for SQW-ASPAT with different Al concentrations.

B. *Double Quantum Well ASPAT*

In the case of AlxGa1-xAS/AlAs DQW-ASPAT, the structure is similar to SQW-ASPAT except for the addition of a QW layer in conjunction with the long space layer as in Table 2. Fig 7 illustrates the conduction band for DQW-ASPAT structure at different Al concentrations in long spacer. The presence of a sandwich barrier between two layers of QW reduces the current passing through the tunnel while also reducing the asymmetry between the forward and reverse currents. On the other side, increasing the Al concentration in the long space increases the asymmetry between the forward and reverse currents by altering the conduction band's discontinuity. Regarding the I-V curve, it observe that the asymmetry between the forward and reverse currents is low when the Al concentration is low as illustrated in Fig 8. However, the asymmetry increases significantly with increasing Al concentration in the long space. Nevertheless, the current through the tunnel is greater compared to the SQW-ASPAT. This increasing in the current due to the presence of a quantum resonance phenomenon across the barrier, which occurs because of the formation of a repeated quantized energy levels. This phenomenon increases the probability of electrons permeability.

Table 2 The Characteristics of AlxGa1-xAS/AlAs DQW-ASPAT diode structure.

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)	5	1×10^{14}
$In_{0.18}Ga_{0.82}As$(QW)	6	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}

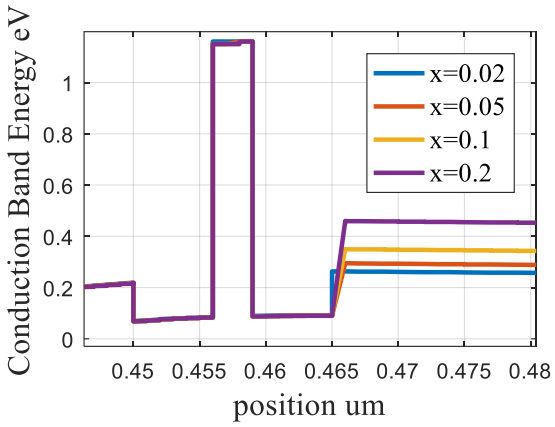

Fig 7 The conduction band diagram of AlxGa1-xAS/AlAs DQW-ASPAT structure with different Al compositions.

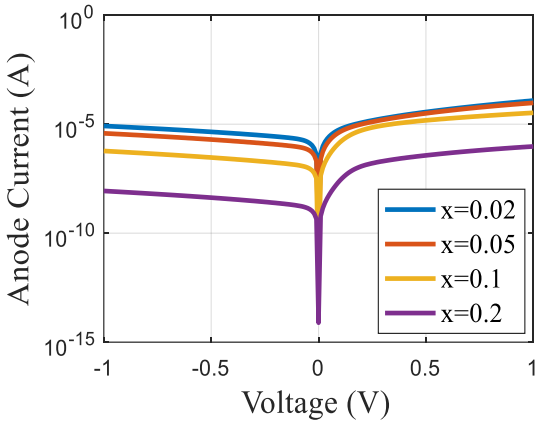

Fig 8 I-V curve of AlxGa1-xAS/AlAs DQW-ASPAT structure with different Al compositions.

As a result of increased asymmetry with increasing Al concentration in long space, this behavior is reflected to the Kv value. Fig 9 shows the relationship of the curvature coefficient with the change in Al concentration in the long space in the DQW-ASPAT structure. Increasing the concentration of Al alters the discontinuity of the conduction band in the long-space direction, which increases the obstacles to the reverse current, causing an increase in the curvature coefficient.

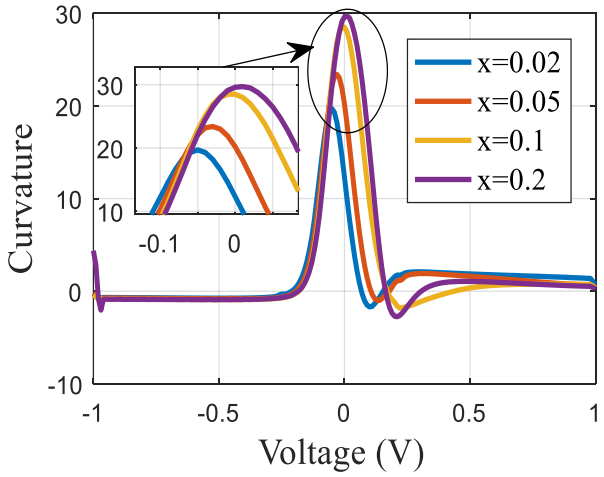

Fig 9 Curvature Coefficient of AlxGa1-xAS/AlAs DQW-ASPAT structure with different Al compositions.

One of the advantages of the DQW-ASPAT design is the reduction of junction resistance. Fig 10 shows the effect of changing the Rj value when the Al concentration is changed. Compared to the results obtained with SQW-ASPAT, the junction resistance is significantly lower with the presence of an additional QW layer. Since the value of the junction resistance depends on the inverse of the first derivative of the current ($R_j = 1/(\partial i/\partial V)$), a larger current flow means that the value of the resistance will be lower.

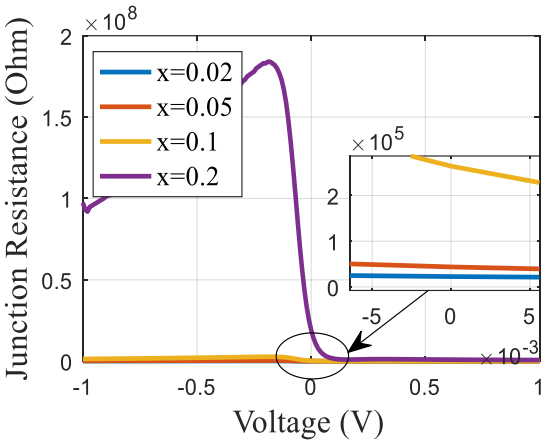

Fig 10 Curve of junction resistance of AlxGa1-xAS/AlAs DQW-ASPAT structure with different Al compositions.

Fig 11 shows the Junction capacitance of AlxGa1-xAS/AlAs DQW-ASPAT structure with different Al compositions. It clear that an improvement compare with SQW-ASPQT by reducing the value of Cj.

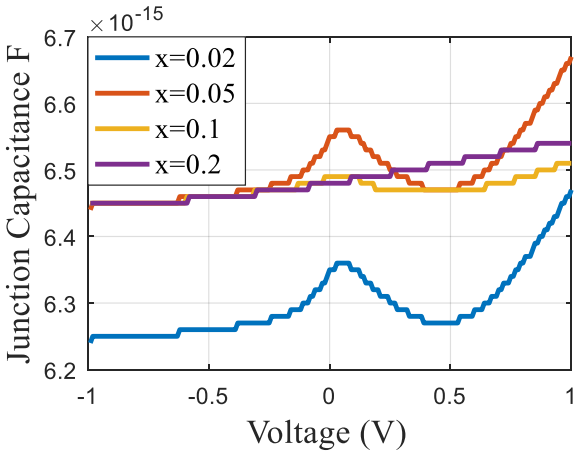

Fig 11 Junction capacitance of AlxGa1-xAS/AlAs DQW-ASPAT structure with different Al compositions.

Table 3 shows the cut-off obtained for both designs at different concentrations of Al. AS cut-off frequency entirely depends on the value of junction resistance (1/(2πCjRs)), the cut-off frequency limits for DQW-ASPAT is higher compare with SQW-ASPAT structure at the same Al concentration at long spacer.

Table 3 cut-off obtained for AlxGa1-xAS/AlAs DQW-ASPAT&SQW-ASPAT structures.

x-Comp.	C_j (fF)		F_c(GHz)	
	SQW	DQW	SQW	DQW
0.02	7.2	6.2	315	372
0.05	6.9	6.5	329	354
0.1	6.8	6.48	326	349
0.2	6.6	6.48	321	342

C. *Result of RF detector with equevalent circuit*

The ADS software is used to determine the benefit of adding an extra QW layer at different Al concentrations in long space. ADS does not include a built-in ASPAT model, so the SDD block is used to represent ASPAT models as a set of equations. These equations are obtained using MATLAB software via the polyfit command. Fig 12 illustrates the RF detector circuit with its equivalent ASPAT circuit implemented using ADS. ASPAT can be represented by using the SDD block in parallel with Cj, which is in series with the device's serial resistor (Rs). The receiver circuit also includes an equivalent antenna circuit (P_1 Tone) with input impedance Z=50Ω, a matching circuit (DA_SmithChartMatch1) that ensures maximum power is transferred from the antenna to the ASPAT. The load circuit built by 25KΩ resistor in parallel with 0.1pF capacitance.

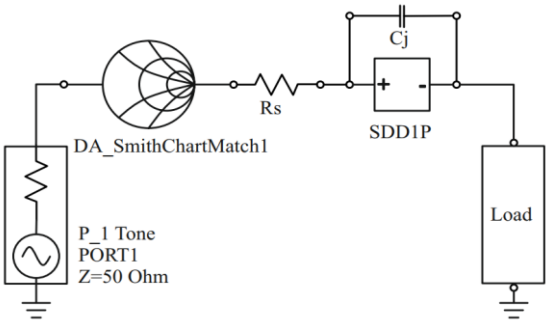

Fig 12 The receiver Circuit designed by ADS environment with equivalent circuit of ASPAT.

Sensitivity is one of the most important criteria that determines the quality of a detector. Based on the following equation, the curvature coefficient is the most important factor in determining the detector's sensitivity [7].

$$\beta_v = 2ZK_v(1 - |\Gamma|^2) \quad (2)$$

When β_v is actual sensitivity, Z is the source impedance, and Γ is reflection coefficient.

Fig 13 illustrates the sensitivity of the SQW-ASPAT design at different Al substrates in the long space. It observe an improvement in sensitivity as the Al concentration increases due to the increasing curvature coefficient.

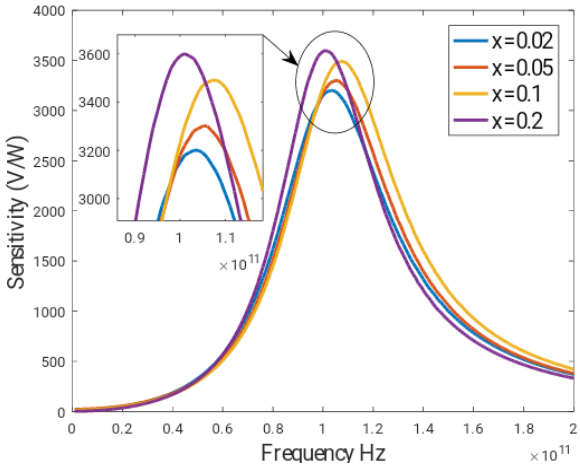

Fig 13 Sensitivity of RF detector with AlxGa1-xAS/AlAs for SQW-ASPAT with different Al concentrations.

Fig 14 illustrates the relationship between the received power and the output voltage of the detector. It can be said that the detector's ability to handle lower power signals increases with a lower Al concentration. In fact, the main reason for this behavior return to the value of junction resistance. On other description, when the Rj value is low, the detector can detect low-power signals, and vice versa.

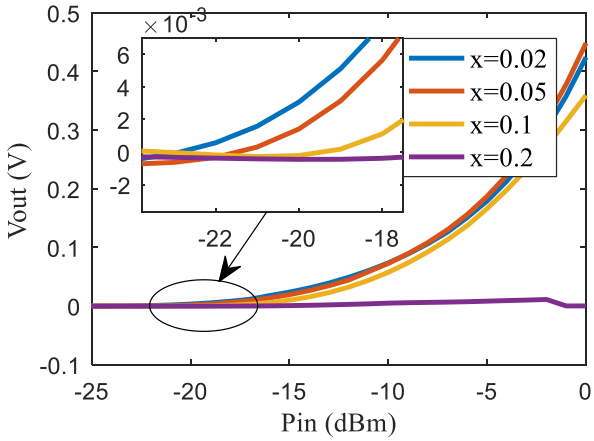

Fig 14 Pin-Vout curve for RF detector with AlxGa1-xAS/AlAs for SQW-ASPAT with different Al concentrations.

Fig 15 illustrates the sensitivity curve for the DQW-ASPAT architecture at various long space Al concentrations. Compared to the obtained results of the SQW-ASPAT design, it observed that a clear advantage for the design containing a single QW layer. This advantage stems from the superiority of the curvature coefficient, which is a sensitivity criterion in RF detectors. Furthermore, Fig 16 shows the relationship between input power and output voltage based on the DQW-ASPAT detector configuration. It observe that the DQW-ASPAT can detect signals with lower power compared to the design containing a single QW layer. This improved detection capability for low-power signals is due to the presence of an additional QW layer. In another words, depending on presence of low junction resistance in DQW-ASPAT design, this feature increases the ability of the device to detect low power signals.

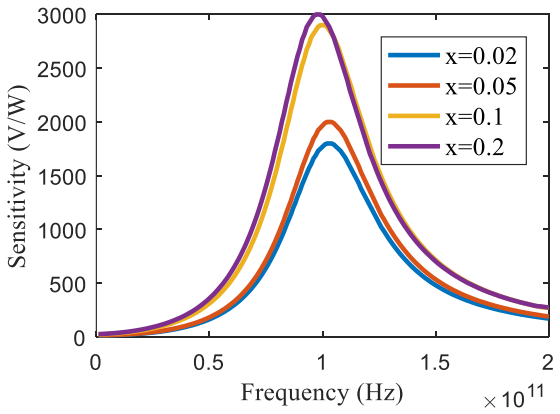

Fig 15 Sensitivity of RF detector with AlxGa1-xAS/AlAs for DQW-ASPAT with different Al concentrations.

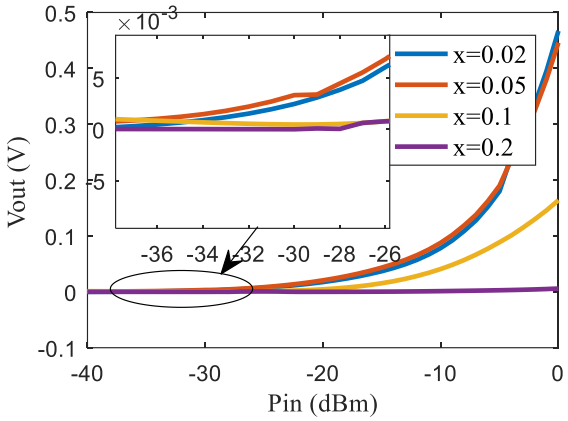

Fig 16 Pin-Vout curve for RF detector with AlxGa1-xAS/AlAs for SQW-ASPAT with different Al concentrations.

CONCLUSION

The presence of a QW layer in conjunction with the ASPAT allows this device to improve its curvature coefficient, making it competitive with SBDs. The curvature index can also be improved by modifying the long space discontinuity through the use of AlxGa1-xAs with increasing Al concentration. However, increasing the Al concentration in the long space results in a significant increase in the junction impedance, which negatively impacting the detection of low power signals. To address this issue, a second QW layer is added, which reduces the junction impedance and improving the detector to detect low power signals.

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