Schottky contact diameter effect on the electrical properties and interface states of Ti/Au/p-AlGaAs/GaAs/Au/Ni/Au Be-doped p-type MBE Schottky diodes

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**Abstract**

Schottky diodes based on Be-doped p-type AlGaAs were grown by molecular beam epitaxy (MBE) and their current-voltage (I-V) and capacitance-voltage (C-V) characteristics measured. The Schottky and Ohmic contacts are Ti/Au and Au/Ni/Au, respectively. The effect of the Schottky contact diameter on I-V and C-V characteristics was studied. To elucidate this effect, the Schottky diode figures of merits and interface states are extracted from I-V and C-V characteristics, respectively. It was found that interface states density increases with increasing Schottky contact diameter then saturates beyond 400 µm. The frequency dependence of the C-V characteristics was also related to these interface states. The results of this present study can help choosing the right Schottky contact dimensions.

Keywords:

p-type AlGaAs ; Schottky diode; interface states; electrical characteristics; Schottky contact diameter.

## 1. Introduction

Schottky contacts are commonly used in a wide variety of semiconductor devices for different applications as well as a tool for investigating the physical and electrical properties of a semiconductor [1,2]. Thus, this structure is extensively studied both experimentally and theoretically [3]. GaAs and AlGaAs are important semiconductors for developing several applications of Schottky diodes including high speed devices [4], high electron mobility transistors (HEMTs) [5], solar cells [6], betavoltaic cells [7] and particle detectors [8]. Schottky barriers are usually realised by depositing a layer of a metal on a semiconductor without considering lattice mismatching amongst other conditions [9]. It is therefore expected that native defects, referred to as interface states, are generated. These have drastic effects on Schottky based devices. For example, variations of the electrical characteristics with frequency and temperature are related to inhomogeneities of the Schottky barrier which are related to interface states. The performance and reliability of a Schottky contact are therefore highly affected by the interface quality between the metal and the semiconductor. Possible anomalies have been proposed by taking into account the interface state density distribution [10], quantum-mechanical tunnelling [11,12] and lateral distribution of the barrier height [13,14]. A Gaussian distribution of the Schottky barrier over the contact area has been also assumed to describe the inhomogeneities [15]. Several approaches have been adopted to reduce interface states including the insertion of an interfacial layer between the metal and the semiconductor [16–18]. Other treatments were also considered. For example, Kanmaz et al. [3] found that annealing the Schottky contact had a profound effect on the diode electrical characteristics and the extraction of the diode's parameters. To evaluate the interface density, the well-known frequency dependent capacitance method is usually used [19]. Kacha  et al. noticed that the Schottky metal material diffuses and induces a strong effect on the electrical parameters and device performances [20]. Özdemir et al.[21] demonstrated that the potential barrier with GaAs decreases with the increase of the thickness of the Schottky. The semiconductor thickness also has an effect on the Schottky diode characteristics and performance [22]. Kraya and Kraya studied the effect of the contact size on the formation of the Schottky barrier and found that the bigger the size the more likely a Schottky contact is obtained [23]. Wang et al. studied the effect of the Schottky contact size on the electrical characteristics of GaN Schottky diodes [24]. In this work, the effect of the Schottky contact diameter on current-voltage and capacitance-voltage characteristics of a Ti/Au/p-AlGaAs/GaAs/Au/Ni/Au Schottky diode is studied. The device should have a minimum leakage current and a large capacitance. The diode figures of merits and interface states are extracted from these characteristics, respectively, and their relation with the Schottky contact diameter is explained.

## 2. Materials and methods

Ti/Au/AlGaAs/GaAs/Au/Ni/Au Schottky diodes were fabricated on a (100) oriented semi-insulating GaAs substrate. The GaAs/AlGaAs epitaxial layers were grown using a Varian Gen-II Molecular Beam Epitaxial (MBE) system at a temperature of 680 °C with an $As_4$ beam-equivalent pressure of $2\times10^{-5}$ Torr. The MBE structure consisted of 0.45 μm undoped GaAs buffer layer followed by a 1 μm thick Be-doped p-type $Al_{0.29}Ga_{0.71}As$ layer. The free carrier concentration was determined from room temperature Hall measurements and was to be $\sim1\times10^{17}$ $cm^{-3}$. The metallization process was carried out using an EDWARDS E306 thermal evaporation system. The Schottky contacts, of different diameters ranging from 250 to 600 μm, were formed by evaporation of Titanium (Ti) and Gold (Au) layers with thicknesses of ~20 and 200 nm, respectively, on top of the AlGaAs layer. The AlGaAs layer was etched to ~600 nm at the edge of the AlGaAs layer in order to deposit the Ohmic contact (Au/Ni/Au) that was annealed at 360 $^{0}$C [25,26]. The fabricated Schottky diode was then mounted onto a T05 header for electrical characterisation. A schematic diagram of the MBE structure and metallisation, and image of the processed samples mounted onto a T05 header are shown in Figure 1 (a) and (b), respectively.

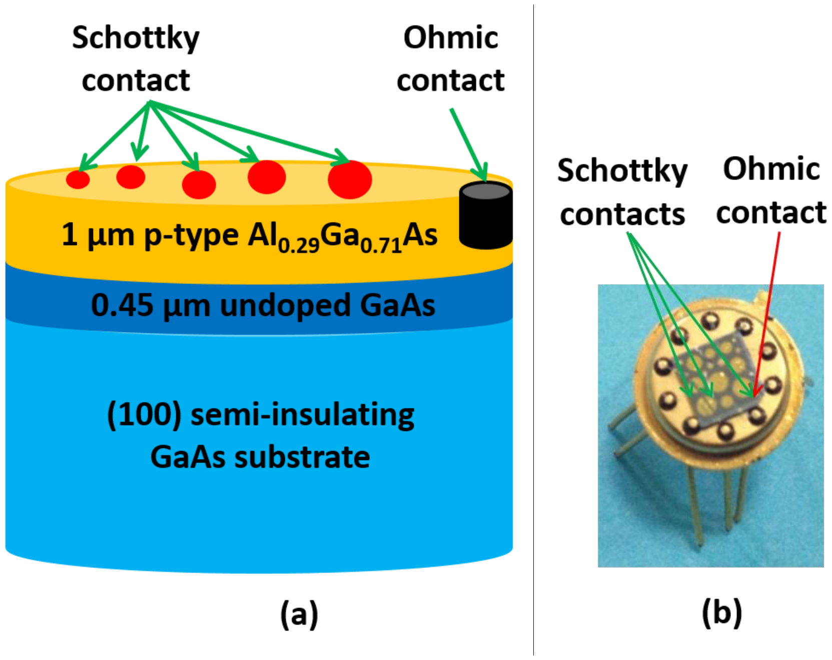


Figure 1. (a) A schematic diagram the MBE structure and metallisation; (b) fabricated Ti/Au/p-AlGaAs/GaAs/Au/Ni/Au Schottky diodes mounted onto a T05 header.

The current-voltage (I-V) and capacitance-voltage-frequency (C-V-f) characteristics are measured using a B1500A Semiconductor Device Parameter Analyser controlled by Easy-Expert software at room temperature.

in a Closed Cycle refrigerator, JANIS CCS-450 controlled by an associated Lakeshore 311 temperature controller

## 3. Results and discussions

### 3.1. I-V characteristics and figures of merits

I-V characteristics of the Schottky diodes are measured at room temperature for different contact diameters. These measurements are shown in Figure 2 (a) and (b) on linear and semi-logarithmic scales, respectively. The diode figures of merits (ideality factor $n$, barrier height $\phi_B$, series resistance $R_S$, on-resistance $R_{ON}$ and the rectifying ratio $\frac{I_F}{I_R}\Big|_{|V|=4\ V}$), extracted from these characteristics, are shown in Figure 2 (c). Parameter extraction is carried out assuming that I-V characteristics obey the simple Schottky equation for thermionic emission given by [27,28]:

$$I = I_s\left(\exp\left(\frac{q(V-R_SJ)}{nK_BT}\right)-1\right) \tag{1}$$

where $I_s$ is the saturation current, $q$ is the elementary charge, $R_s$ is the series resistance and $n$ is the ideality factor. $K_B$ and $T$ are Boltzmann constant and the absolute temperature (K), respectively. In this conduction mechanism, $I_s$ is given by [27,28]:

$$I_s = AA^*T^2 exp\left(-\frac{q\phi_B}{K_BT}\right) \tag{2}$$

where $A$ is the area of the Schottky diode, $A^*$ is the Richardson constant (8.05 A·cm$^{-2}$·K$^{-2}$ [16,29,30]) and $\phi_B$is the Schottky barrier height.

$\phi_B$ and $R_s$ are determined from the modified Norde function, $F(V,T)$, which assumes thermionic emission process [31,32]. From the current-voltage equation, $F(V)$ function is defined as [28,31,32]:

$$F(V) = \frac{V}{2} - \frac{K_BT}{q}\ln\left(\frac{I}{AA^*T^2}\right) = \phi_B + \frac{I.R_S}{n} + V\left(\frac{1}{n}-\frac{1}{2}\right) \tag{3}$$

It can be shown that the barrier height $\phi_B$is given by [28,31]:

$$\phi_B = F_{min}(V) - (\frac{2}{n}-1)\frac{K_BT}{q} + V(F_{min})(\frac{1}{n}-\frac{1}{2}) \tag{4}$$

The ideality factor is calculated from the slope of the linear region of the low forward bias $ln\ (I)$ versus voltage and can be written as [28,31]:

$$n = \frac{q}{K_B T}\left(\frac{dV}{d(\ln(I))}\right) \quad (5)$$

$R_s$ is extracted from $F_{min}(V)$ function as [28,31]:

$$R_s = \frac{(2-n)\ K_B T}{q\ I(F_{min})} \quad (6)$$

where $I(F_{min})$ is the current at $F_{min}(V)$.

The on-resistance $R_{ON}$ is evaluated from the slope in the linear region of the I-V characteristics as shown in Figure 2 (a).

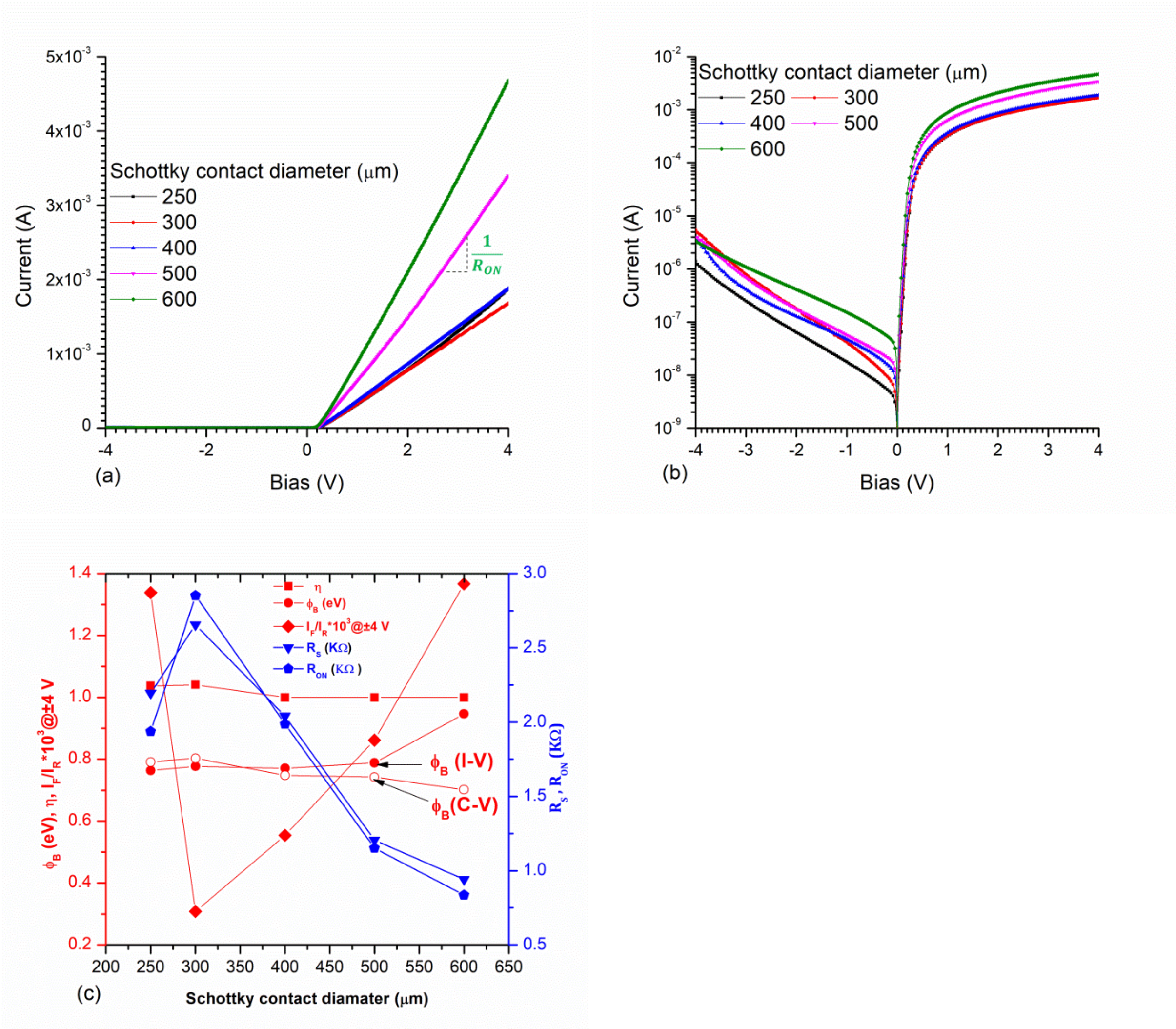


Figure 2. The I-V characteristics on linear and semi-logarithmic scales (a) and (b), respectively, and the extracted figures of merits (c) of the Ti/Au/p-AlGaAs/GaAs/Au/Ni/Au Schottky diodes at room temperature for different Schottky contact diameters. In (c) the barrier height is also deduced from the $C^{-2} = f(V)$ characteristics.

In general the current increases with increasing Schottky contact diameter (and hence its area) which is evident from equations (1) and (2). However, the contact resistance, which contributes to the overall on- and series resistances, decreases with increasing Schottky contact diameter, as observed in Figure 2 (c). Meanwhile, both the ideality factor and the barrier height decreases and increases, respectively, slightly. The rectifying ratio generally increases with increasing Schottky contact diameter (except for the smallest diameters, i.e. 250 µm and 300 µm). This may indicate that the Metal-Semiconductor (MS) junction quality is unaffected. The exceptional behaviour observed in the devices with the smallest diameters is due to interface states as will be explained in the next sub-section when C-V characteristics are analysed and the interface states are extracted. Based on DLTS criteria the best device is 300 µm because the smallest device (250 µm) has the lowest current but the lowest capacitance while the largest device (600 µm) has the largest capacitance but the highest leakage current. The SBD (Single Barrier Diode) figures of merit criteria suggested that the best device is the 500 µm diameter diode.

### 3.2. C-V characteristics and interface states

C-V characteristics of the Schottky diode are measured at room temperature for different contact diameters at low and high frequencies (1 KHz and 1 MHz) in order to extract the interface states distribution. These measurements are shown in Figure 3 (a) and (b) for low and high frequency, respectively. As shown in Figure 3 (b), the capacitance for larger diameters increases slightly with increasing reverse bias voltage at high frequency (1MHz), then decrease in the usual way. This is maybe related to higher interface states density. In the presence of interface states, the equivalent capacitance ($C$) of the diode is a parallel combination of the interface states capacitance $\mathrm{C}_{it}$ and the space charge capacitance $\mathrm{C}_d$ [33,34], given is:

$$C = \mathrm{C}_d + \frac{\mathrm{C}_{it}}{1+(w\tau)^2} \qquad (7)$$

$w = 2\pi f$; $f$ is the frequency and $\tau$ is the interface trap time constant. At low and high frequencies the capacitance is given by [33,34] $C_{LF} = \mathrm{C}_d + \mathrm{C}_{it}$ and $C_{HF} = \mathrm{C}_d$ respectively, so that:

$$\mathrm{C}_{it} = C_{LF} - C_{HF} \qquad (8)$$

The interface state density $N$ss can be obtained from [33,34]:

$$N_{ss} = \frac{C_{it}}{qA} = \frac{C_{LF} - C_{HF}}{qA} \text{ (eV}^{-1}\text{.cm}^{-2}\text{) (F.e}^{-1}\text{.cm}^{-2}\text{)(e.V}^{-1}\text{.e}^{-1}\text{. cm}^{-2}\text{)} \qquad (9)$$

where $q$ is electronic charge, $A = \pi r^2$ is the device area and $r$ is the radius.

The extracted interface states distribution is shown in Figure 3 (c).

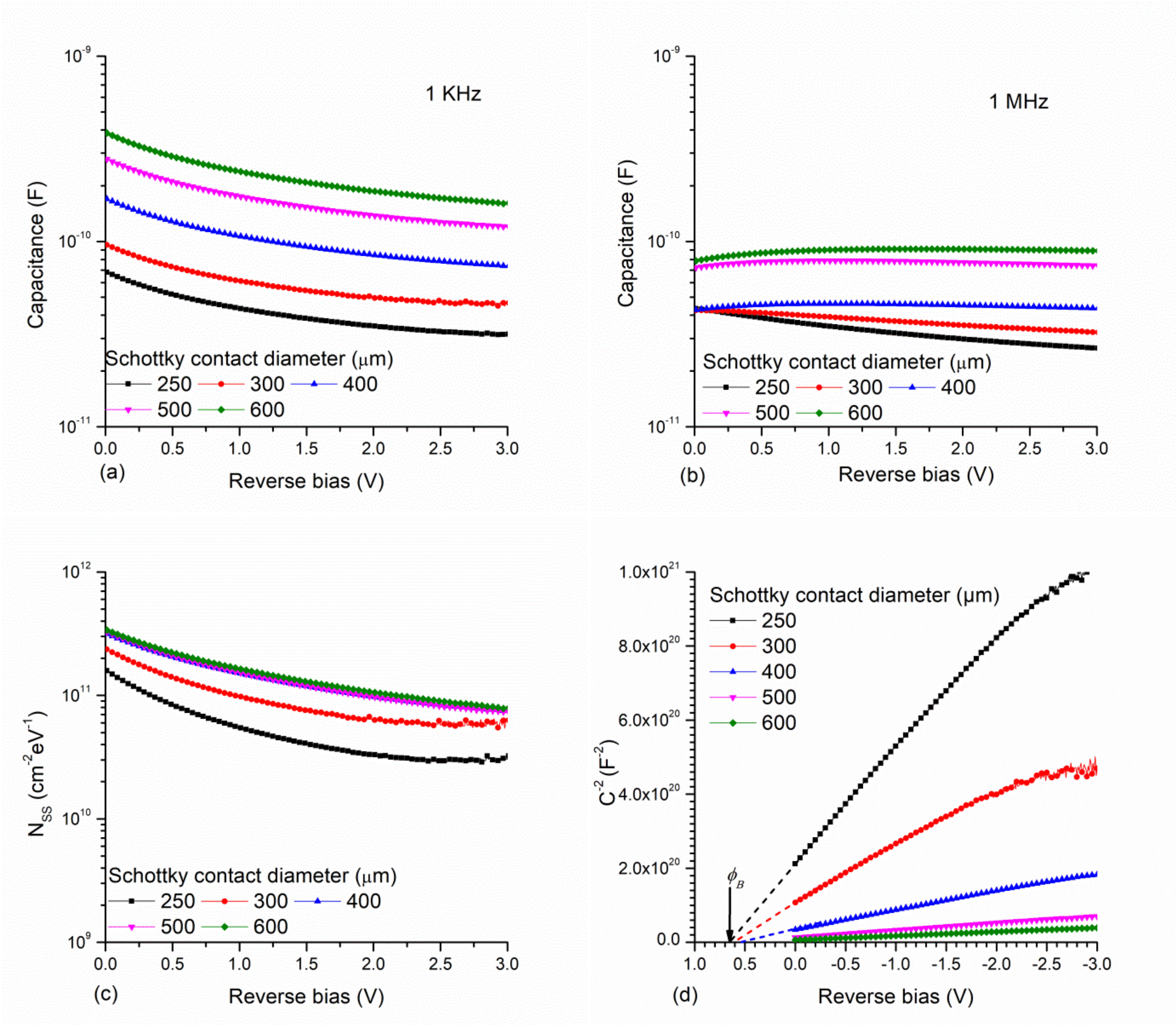


Figure 3. C-V characteristics at low and high frequency (a) and (b), respectively, the extracted interface states (c) and (d) a plot of $C^{-2}$ to extract $\varphi_B$ of the Ti/Au/p-AlGaAs/GaAs/Au/Ni/Au Schottky diodes at room temperature for different Schottky contact diameters.

The capacitance increases with increasing Schottky contact diameter (and hence its area) which is evident from the fact that the MS junction capacitance is directly proportional to its area as [2]:

$$C = A\frac{\varepsilon_r \varepsilon_0}{d} \qquad (10)$$

where $\varepsilon_r$ is the semiconductor relative permittivity, $\varepsilon_0$ the vacuum permittivity and $d$ is the space charge width.

The low frequency capacitance is more sensitive with Schottky contact diameter than its high frequency counterpart. This may be due the presence of interface states (shown in Figure 3 (c)) of which the inverse time constant is just below 1 MHz as shown by the frequency dependent capacitance in Figure 4 (a). At low frequency, all interface states appear to have fully responded (their ionisation is saturated), hence their contribution to the capacitance is saturated. Therefore, the only effect observed is related to the Schottky contact diameter (and hence its area). However, at higher frequencies, interface states are slower to follow the alternating signal. Therefore, the interface states presence is not felt by the measured capacitance. In this case, the Schottky contact diameter and interface states are affecting the capacitance.

This behaviour is further evidenced by DLTS measurement of deep levels as shown in Figure 4 (c) [25]. DLTS reveals two acceptor-like traps labelled HE1 and HE2 with activation energies of 0.021 and 0.13 eV, respectively. These energies indicate that these traps are quite shallow. Therefore, they may well correspond to interface states rather than deep levels. This argument is further strengthened by the fact their DLTS peak is quite broad.

In the following, the effect of interface states on I-V characteristics will be discussed. The current increases with increasing Schottky contact diameter but it saturates for the 400 μm diameter and beyond. The current tends to be more exponential than linear for the 250 μm diameter but its behaviour becomes linear as the diameter increases. Consequently, the extracted parameters are affected by this behaviour.

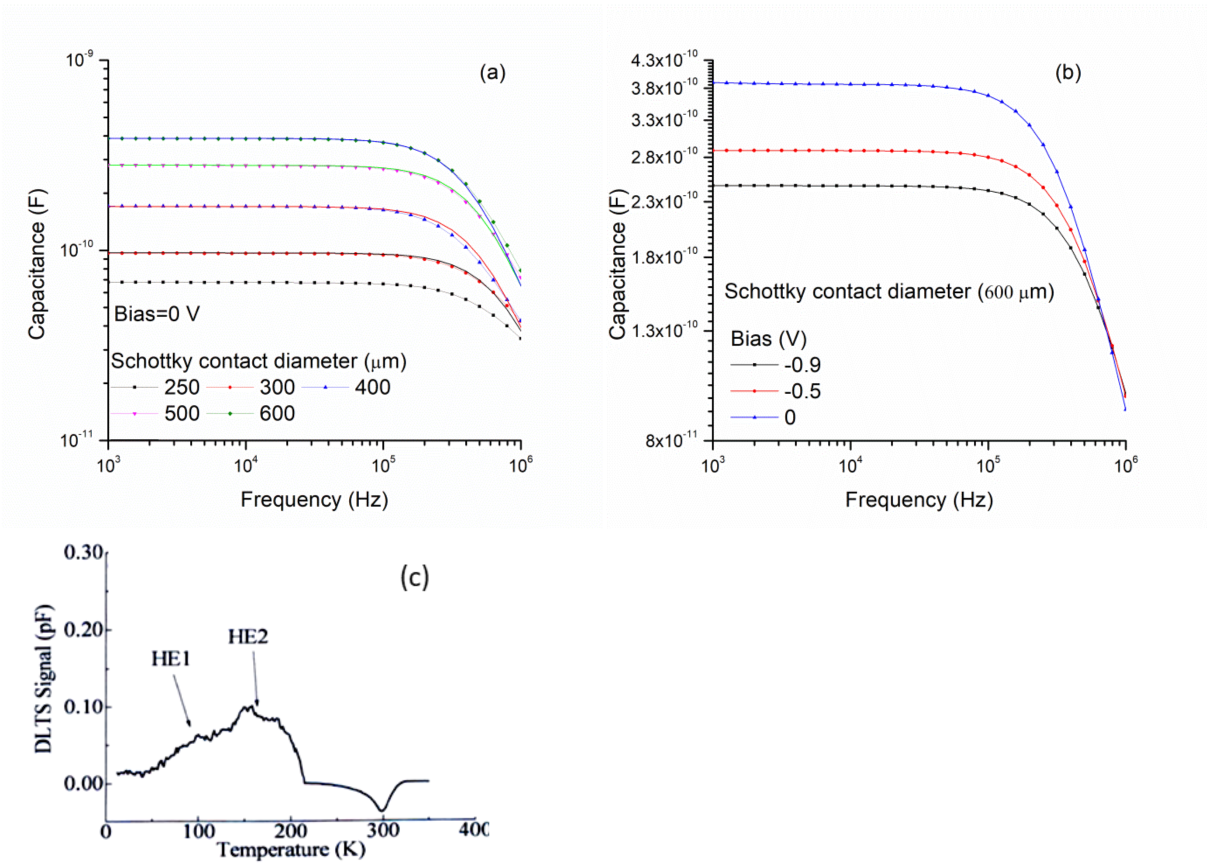


Figure 4. Frequency dependence of room temperature C-V characteristics of Ti/Au/p-AlGaAs/GaAs/Au/Ni/Au Schottky diodes (a) at 0 V and different diameters and (b) at different reverse biases and a diameter of 600µm. (c) DLTS spectrum for deep levels in the diode with 600µm diameter [25]. At higher reverse voltages the contribution of interface states to the capacitance remains saturated up to much higher frequencies than at low or zero reverse bias. This can be due to non-uniformity of interface states. For low reverse bias, the depletion region is small, and therefore it is very close to the interface region while at high reverse bias the depletion region is larger so that it is further away from the interface.

## Conclusion

We investigated the effect of the diameter of Schottky devices on their figure of merits and interfacial states. I-V and C-V characteristics of different diameters Ti/Au/p-AlGaAs/GaAs/Au/Ni/Au Schottky diodes were measured at room temperature. The diode figures of merits (ideality factor $\eta$, barrier height $\phi_B$, series resistance $R_S$ and on resistance $R_{ON}$) were extracted from I-V characteristics. Interface states were obtained from C-V characteristics. It was found that as the Schottky contact diameter increases from 250 to 400 µm, the interface states density increases then saturates for diameters up to 600 µm. The interface states density and the Schottky contact diameter have competing effects on the I-V and C-V-f characteristics. The requirements of the suitability of Schottky diodes for DLTS measurements are large capacitance and low leakage current. However, based on this DLTS criterion, the best device is the 300 µm diameter diode because the smallest device (250 µm) has the lowest current but the lowest capacitance while the largest device (600 µm) has the largest capacitance but the highest leakage current. Further work is required to investigate the detailed effect of frequency and its relation to the Schottky contact.

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**Conflict of interest**

There are no conflicts of interest in this article.

**Data availability**

Data sharing is not applicable to this article as no new data were created or analysed in this article.

**Ethics statement**

There are no ethic issues in this article.

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