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ANOMALOUS CAPACITANCE OF GaN-BASED SCHOTTKY DIODES

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Abstract: The capacitance-voltage (*C-V*) measurements of GaN-based Schottky diodes were carried out in the frequency range of 0.3 ~ 1.5MHz. Anomalous peaks and negative value of capacitance were observed in the *C-V* plots of Au/i-GaN Schottky diodes under forward bias, while neither of them was seen in the plots of Au/i-$Al_{0.45}Ga_{0.55}N$ Schottky diodes. Based on the parameters extracted from the current-voltage (*I-V*) and *C-V* plots of GaN and $Al_{0.45}Ga_{0.55}N$ Schottky diodes, the peak and negative capacitance are ascribed to the capture and loss of interface charges. These processes are greatly suppressed when there exists a huge series resistance in the diode.
Key words: capacitance-voltage characteristic; Schottky diode; GaN-based material
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GaN基肖特基器件中的反常电容特性

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摘要:研究了测试频率为0.3~1.5MHz时GaN基肖特基器件的电容特性.实验发现,在Au/i-GaN肖特基器件的电容-电压(*C-V*)特性曲线中,出现了峰和负值电容,而Au/i-$Al_{0.45}Ga_{0.55}N$肖特基器件的*C-V*特性曲线中则既没有峰也没有负值电容的出现.对肖特基器件的电流-电压(*I-V*)特性和*C-V*特性进行参数提取和分析后认为,负值电容和峰的出现源于界面态的俘获和损耗,但较大的串联电阻将减弱界面态的作用.
关 键 词:电容-电压特性;肖特基器件;GaN基材料

Introduction

In the past decade, GaN and related Ⅲ-nitrides compounds have attracted a great deal of interest because of their potential application in high temperature, high power and high frequency electronic devices[1]. Among all kinds of GaN-based UV photodetectors, Schottky diodes have several advantages, such as simplicity of fabrication, flat response and high-speed operation[2]. The electrical characteristics such as current-voltage (*I-V*) curves of Schottky devices are often modified by many non-idealities such as interface states, interface layer, and series resistance[3~5]. Capacitance-voltage (*C-V*) characteristics of Schottky contacts are often used for determining parameters such as doping content of semiconductor, barrier height of Schottky contact, and series resistance[4,5]. They are often helpful in evaluating the profiles of deep levels in semiconductors and the 2DEG concentrations at heterostructure interfaces[6,7]. However, novel peaks and negative capacitance in the forward bias *C-V* plots of Schottky diodes made of different materials have been reported and their origins have been argued by many researchers[8~12]. The conformity between all researchers hasn't been achieved so far because the frequency characteristic of Schottky diodes is sensitive to material

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quality, preparation process, measurement condition, etc. In this research, both Au/i-GaN and Au/i-$Al_{0.45}Ga_{0.55}N$ Schottky diodes were prepared with almost the same procedure, but their *C-V* characteristics differ considerably with each other. To explain the difference between the Au/i-GaN and Au/i-$Al_{0.45}Ga_{0.55}N$ Schottky diodes, the series resistances were extracted from their current-voltage (*I-V*) plots.

1 Experiments

The i-n^+ photodiode wafers were grown by metal-organic chemical vapor deposition on sapphire substrate polished on both sides. The schematic diagrams of diode structures are shown in Fig. 1. To remove any native oxide and contamination, the samples were dipped into alcohol/hydrochloric acid solution for 8 min. Before making metal contacts, the samples were immersed in boiling KOH solution to remove the etching damage. For GaN diodes, the Schottky contacts were made by evaporating Au to i-GaN layer and the Ohmic contacts were made by evaporating Ti/Al/Ti/Au to n^+- GaN layer, and no thermal treatment was made for the contacts. For $Al_{0.45}Ga_{0.55}N$ Schottky diodes, the two contacts were made in the same way with an additional annealing in nitrogen at 750℃ for 30 s. Mesa structures were prepared by standard photolithography and dry etching. *I-V* measurements were performed using KEITHLEY 236 source measure unit, and frequency-dependent *C-V* measurements were finished with HEWLETT 4194A parameter analyzer.

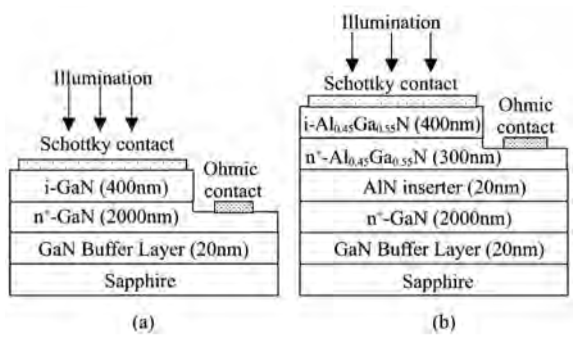

Fig. 1 Schematic diagrams of the GaN-based Schottky diodes (a) Au/i-GaN, (b) Au/i-$Al_{0.45}Ga_{0.55}N$
图 1 (a) Au/i-GaN 和(b) Au/i-$Al_{0.45}Ga_{0.55}N$ 肖特基器件的结构图

2 Results and discussion

The forward and reverse-biased *I-V* measurements of the GaN and $Al_{0.45}Ga_{0.55}N$ Schottky diodes were carried out at room temperature. Their *I-V* characteristics are given in Fig. 2. According to the thermionic emission (TE) model, the current through a barrier can be expressed as[4,5]

$$I = I_s\left[\exp\frac{q}{nkT}(V - IR_s)\right] \quad , \tag{1}$$

where I_s is the reverse saturation current and can be expressed as

$$I_s = A_{eff}A^* T^2 \exp\left(-\frac{q\phi_B}{kT}\right) \quad , \tag{2}$$

where n is the ideality factor, V is the applied voltage, IR_s is the voltage drop across series resistance of the device, A_{eff} is the effective diode area, A^* is the Richardson constant which equals to 26.4 A/cm^2K^2 for i-GaN and 52.8/cm^2K^2 for i-AlN, T is the temperature in K, and ϕ_B is barrier height at zero bias.

It can be seen that the semi-logarithmic *I-V* characteristic of the GaN and $Al_{0.45}Ga_{0.55}N$ Schottky diodes under forward and reverse bias show good rectifying behavior at room temperature. Moreover, the not-saturating behavior was observed as a function of bias in the reverse bias branch, which may be explained by the image force lowering of Schottky barrier height and the interfacial layer between the metal and semiconductor[5]. In general, the forward-bias *I-V* characteristics are linear on a semi-logarithmic scale at low forward-bias voltages but deviate from linearity due to the effect of series resistance R_s, the interfacial layer, and interfacial states when the applied voltage is sufficiently large. The series resistance indicates its existence by the downward curvature of the forward-bias *I-V* characteristics, while the other two are responsible for both linear and non-linear characteristics of the *I-V* curves. Therefore, n, ϕ_B, R_s were calculated by the method developed by Cheung and Cheung[13]. According to this method, from equation (1) we can get

$$\frac{dV}{d(\ln J)} = R_s A_{eff} J + n\frac{kT}{q} \quad , \tag{3}$$

$$H(J) = V - n\left(\frac{kT}{q}\right)\ln\left(\frac{J}{A^* T^2}\right) \quad , \tag{4}$$

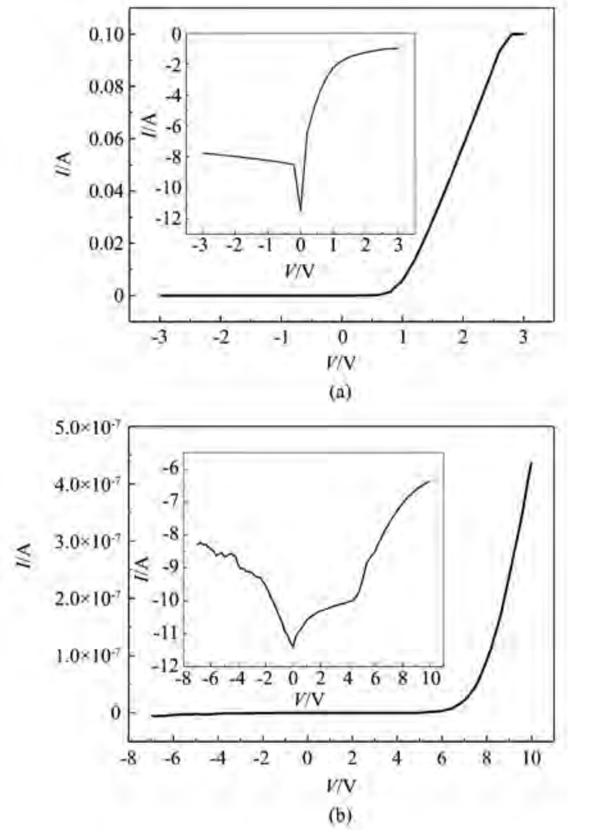

Fig. 2　The current-voltage characteristics of (a) Au/i-GaN and (b) Au/i-$Al_{0.45}Ga_{0.55}N$ Schottky diodes at room temperature. The insets are the corresponding semi-logarithmic *I-V* plots
图 2　(a) Au/i-GaN 和 (b) Au/i-$Al_{0.45}Ga_{0.55}N$ 肖特基器件室温下的 *I-V* 特性

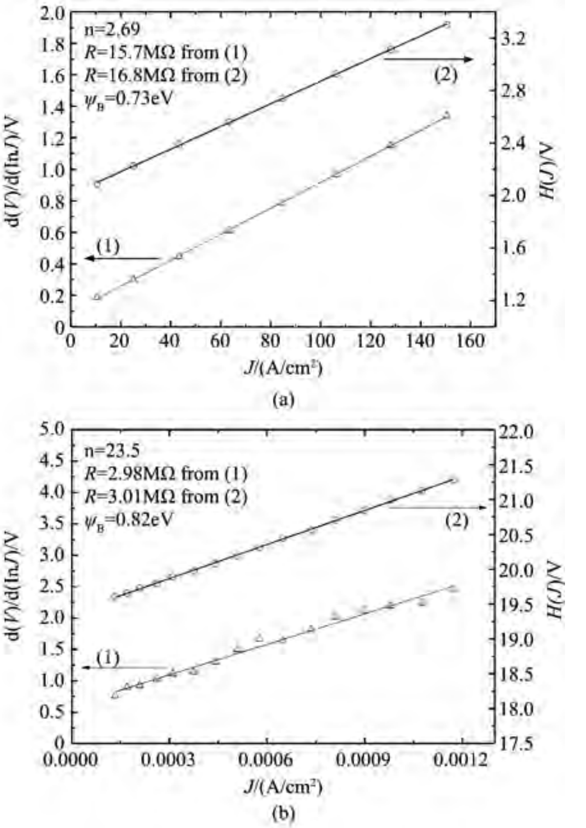

Fig. 3　Experimental dV/d(ln*J*) vs. *J* and *H*(*J*) vs. v*J* plots of (a) Au/i-GaN and (b) Au/i-$Al_{0.45}Ga_{0.55}N$ Schottky diodes
图 3　(a) Au/i-GaN 和 (b) Au/i-$Al_{0.45}Ga_{0.55}N$ 肖特基器件的 d*V*/d(ln*J*)-*J* 以及 *H*(*J*)-*J* 图

and $H(J)$ is given as

$$H(J) = R_s A_{eff} J + n\phi_B \quad . \tag{5}$$

Eq. (3) should give a straight line for the data of downward curvature region in the forward-bias I-V characteristic. So that, a plot of $dV/d \ln J$ vs. J will give R_s as the slope and nkT/q the intercept. Using the n value got from Eq. (3) and the downward-curvature region in Eq. (4), a plot of $H(J)$ vs. J according to Eq. (5) will also give a straight line with the slope of the straight line R_s and the y-axis intercept $n\phi_B$. These graphs and the obtained values of n、ϕ_B、R_s from these graphs are given in Fig. 3.

As can be seen from Fig. 3(a), the n value of GaN Schottky diodes is 2.69, which exceeds its theoretical value falling between 1 and 2. If n is closer to 1, diffusion current dominates; however, if n is closer to 2, then recombination current dominates. $n = 2.69$ falls slightly outside of this expected range, suggesting that an additional process makes a significant contribution to the conduction. This nonideal behavior has been attributed to the tunneling conduction in III nitrides. Both d*V*/d(ln*J*) vs. *J* and *H*(*J*) vs. *J* plots give straight lines and the values of series resistances of GaN-based Schottky diodes extracted from them are in good agreement with each other. However, the n value and series resistance of $Al_{0.45}Ga_{0.55}N$ Schottky diodes shown in Fig. 3 (b) are considerably lager than those of GaN Schottky diodes. The series resistance derived from d*V*/d(ln*J*) vs. *J* and *H*(*J*) vs. *J* plots are 2.98 MΩ and 3.01 MΩ respectively. The n value of $Al_{0.45}Ga_{0.55}N$ diodes is 23.5, which derivates largely from the theoretical value.

As the *Rs* and n values of $Al_{0.45}Ga_{0.55}N$ are abnormally large, double logarithmic *I-V* graph of the diode in forward bias is shown in Fig. 4 in order to understand mechanisms that control the behavior of the Au/i-$Al_{0.45}Ga_{0.55}N$ Schottky diodes. It is clear that the double logarithmic *I-V* plot is separated by three distinct linear regions. In the first region at $V<0.6\text{V}$, an Ohmic relationship ($I \propto V$) is observed, which obeys the equation $J=q\mu n_0 V/d$, where n_0 is the concentration of the free charge carriers in the $Al_{0.45}Ga_{0.55}N$, μ is the mobility of charge carrier in the film, and d is the thickness of the film. In the second region with V in the range of 0.6 ~ 0.9V, the current rises quickly with a relationship of $I \propto V^m$ (with m up to ~13). In the third region the plot has a slope of about 2, which means that the slope of the curve decreases at higher voltage because the device approaches the trap filled limit.

Fig. 4 shows the power law behavior of the current ($I \propto V^m$) with different values of exponent m. It is known as space-charge-limited current (SCLC) conduction[15]. That means, the injected carriers in $Al_{0.45}Ga_{0.55}N$ through the Ohmic contact are trapped by the trapping centers created by impurities and defects in III nitrides, and the current transport in $Al_{0.45}Ga_{0.55}N$ Schottky diodes is governed by the trapped-charge-limited current. That is, the electrical characteristics of $Al_{0.45}Ga_{0.55}N$ Schottky diodes are not only controlled by the contacts, but also by the concentration and the distribution of the trap centers in $Al_{0.45}Ga_{0.55}N$.

The *C-V* characteristics are one of the fundamental properties of the Schottky diodes. For an idealized Schottky diode, the *C-V* characteristics often show an increase in capacitance with the increase of forward voltage that is independent on frequency. However the capacitance in the *C-V* characteristics may be influenced by the non-idealities. Fig. 5 shows the experimental *C-V* characteristics of Au/i-GaN and Au/i-$Al_{0.45}Ga_{0.55}N$ Schottky diode as a function of applied voltage at different frequency. As can be seen from Fig. 5 (a) that the *C-V* characteristics of GaN Schottky diodes have anomalous peaks and negative values. The peak value of the capacitance decreases and the peak shifts toward lower voltage with increasing frequency. As a comparison, the capacitance of $Al_{0.45}Ga_{0.55}N$ Schottky diodes increases with increasing applied voltage monotonically at all frequencies.

It is well known that the capacitance of Schottky barrier diode is extremely sensitive to the interface properties because some interface states cannot response when the frequency is high enough. The existence of peak and negative capacitance in the forward *C-V* plot has been found and their origins have been argued by many researchers. Ho *et al.*[9] firstly found peaks in their Pd/Si Schottky diodes, and Wu *et al.*[8]

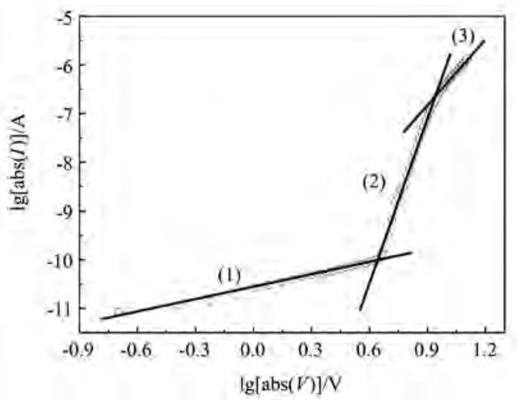

Fig. 4 Log-log plots of *I-V* characteristics for Au/i-$Al_{0.45}Ga_{0.55}N$ Schottky diodes
图 4 Au/i-$Al_{0.45}Ga_{0.55}N$ 肖特基器件的 lg*I*-lg*V* 曲线

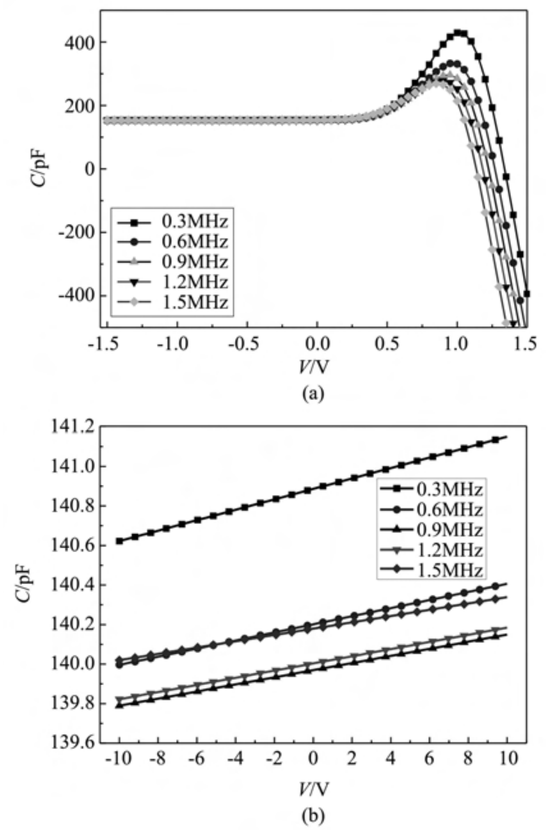

Fig. 5 *C-V* characteristics of (a) Au/i-GaN and (b) Au/i-$Al_{0.45}Ga_{0.55}N$ Schottky diodes
图 5 (a) Au/i-GaN 和 (b) Au/i-$Al_{0.45}Ga_{0.55}N$ 肖特基器件的 *C-V* 曲线

reported peaks and negative capacitance in their Si-based Schottky diodes. Both of them attributed the phenomena to the interface states, and Wu ascribed the negative capacitance to the loss of interface charge at occupied sates below Fermi level due to impact ionization. But their opinion were rebutted by Werner *et al.* [10], who attributed the peaks and negative capacitance to the injection of minority carriers into the bulk semiconductor, which depends sensitively on the properties of the Ohmic back-contact. Champness *et al.* [11] also found anomalous negative capacitance in their Tl/Se Schottky diodes and they hold the similar opinion with Werner *et al.* A moderate group between the above two factions is Muret *et al.* [12], who integrated interface states originating from extrinsic defects localized near the interface and bulk effects in imperfect Ohmic contact to explain their experimental results.

To express the results clearly, series resistances are extracted from the peaks of the *C-V* plots of GaN Schottky diodes. The high frequency capacitance of Schottky diodes can be defined as[14]

$$C = \frac{\mathrm{d}|Q_{sc}|}{\mathrm{d}V} = \left(\frac{\mathrm{d}|Q_{sc}|}{\mathrm{d}\psi_s}\right)\left(\frac{\mathrm{d}\psi_s}{\mathrm{d}V}\right) \quad , \qquad (6)$$

where $Q_{sc} = (2q\varepsilon_s N_D \psi_s)^{1/2}$ is the depletion layer charge density, ψ_s is the surface potential and can be given as

$$\psi_s = \phi_B - v_n - \frac{V - IR_s}{n} \quad , \qquad (7)$$

where v_n is the depth of the Fermi level below the conduction band, ε_s and N_D are the permittivity and doping concentration of the active layer, respectively. From (1)、(2)、(6)、(7), and at the minimum $\mathrm{d}(C^{-2})/\mathrm{d}V = 0$, the series resistance can be given as:

$$R_s = \frac{1}{I_m}\left[\frac{nkT/q}{4} - \frac{n(\phi_B - v_n - V_m/n)}{2} + \frac{1}{4}\frac{nkT}{q} \times \left\{9 - \frac{4(\phi_B - v_n - V_m/n)}{kT/q} + \frac{4(\phi_B - v_n - V_m/n)^2}{(kT/q)^2}\right\}^{1/2}\right] \quad , \qquad (8)$$

where I_m and V_m are the d. c. current and voltage at the capacitance maximum. Using the above method, the series resistances R_s of GaN Schottky diode at different frequency were obtained and given in Table 1. The maximal capacitance values, the voltages V_m at capacitance maximum corresponding to each frequency in Fig. 5(a), and the relevant I_m are also shown in Table 1. It is seen that the value of series resistance is relatively stable in the range of 0.3 ~ 0.9MHz. As the frequency increases, the peak value of capacitance decreases with an increasing series resistance R_s value. According to Wu *et al.*'s charge delocalization model, the electrons that surmount the Schottky barrier under forward bias do fill up the empty states. But they also can knock electrons trapped at the interface states out of the traps considering they possess excess energy. We hold that the interface states in equilibrium with the semiconductor can follow the frequency under the forward bias at low frequency, and can trap relatively more hot electrons trying to surmount the Schottky barrier than at high frequency. The effect of series resistance is suppressed by the interface states when the frequency is rather low. As the frequency increases, the interface states cannot follow the frequency gradually and the effect of series resistance becomes evident. Thus, the series resistance extracted from *C-V* plot at 1.5 MHz is in perfect agreement with that obtained from *I-V* plot using Cheung's method. What is more, the current in the diodes gets high; the interface states which captured hot electrons become saturated as the applied forward voltage increases, and the capacitance gets its peak. Then the knockout of the interface course becomes eminent, the interface loses its trapped electrons, and the capacitance becomes negative.

As to the *C-V* characteristics of $Al_{0.45}Ga_{0.55}N$ Schottky diodes in Fig. 5(b), the slope of the *C-V* plots is nearly the same in the range of 0.3 ~ 1.2MHz, but has a change at 1.5MHz. This change is because the interface states cannot response at high frequency. Fig. 5(b) shows that there is no peak or negative

表 1 Experimental values obtained from the forward bias *I-V* and *C-V* characteristics of the GaN Schottky diodes

Table 1 从 GaN 肖特基器件的 *I-V* 和 *C-V* 曲线中提取的器件参数

f (MHz)	C (pF)	V_m (V)	I_m (A)	R_s (Ω)
0.3	429	1	0.00571	7.96
0.6	332.4	0.95	0.00471	8.92
0.9	296	0.95	0.00471	8.92
1.2	278	0.9	0.0037	10.6
1.5	269	0.85	0.00236	15.5

capacitance in the plots. It is thought that the electrical properties of $Al_{0.45}Ga_{0.55}N$ Schottky diodes are controlled by the high concentration of trap centers and impurities in $Al_{0.45}Ga_{0.55}N$. From Fig. 2 it can be seen that the current in GaN Schottky diodes comes to 0.01A when the applied voltage is only 2.5V, but the current in the $Al_{0.45}Ga_{0.55}N$ diodes is only 10^{-6}A when the applied voltage is 10V. This weak current means that the number of electrons which can cross the Schottky barrier is very small, and only a tiny number of electrons can be trapped by the interface states, and this tiny number is far and away from the number needed to saturate the interface states. So that, there will be no peaks in the *C-V* plots of $Al_{0.45}Ga_{0.55}N$ diodes, not to speak of negative value.

3 Conclusions

In summary, peaks and negative capacitance in the Au/i-GaN Schottky diodes were observed, but none of them was found in the Au/i-$Al_{0.45}Ga_{0.55}N$ Schottky diodes. In order to explain the experimental results, series resistances for both kinds of diodes were extracted from their *I-V* plots by Cheung and Cheung's method. The series resistance of Au/i-GaN Schottky diodes is in good agreement with the result extracted from its *C-V* plots at 1.5MHz. It is concluded that the peaks and negative capacitance in the Au/i-GaN Schottky diodes are caused by the trap and knockout of electrons at the Schottky interface. When the frequency is low, the role of interface states is more significant than the series resistance, and the peak capacitance value is greater than the value when the frequency is high. But when the current in the diodes is controlled by the traps and impurities of III nitrides and the series resistance is huge enough, neither peak nor negative capacitance could be found in the Au/i-$Al_{0.45}Ga_{0.55}N$ Schottky diodes. In this case, there were not enough electrons to be trapped or to be knocked out of the Schottky interface.

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