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Efficacy of ECR-CVD silicon nitride passivation in InGaP/GaAs HBTs

L. B. Zoccal, J. A. Diniz, I. Doi, and J. W. Swart
School of Electrical and Computer Engineering (FEEC), UNICAMP, 13083-970 Campinas, Sao Paulo, Brazil and Center for Semiconductor Components (CCS), UNICAMP, 13083-870 Compinas Sao Paulo, Brazil

A. M. Daltrini[a] and S. A. Moshkalyov
Center for Semiconductor Components (CCS), UNICAMP, 13083-870 Campinas, Sao Paulo, Brazil

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High quality passivation silicon nitride films have been obtained requiring no surface pretreatment and being fully compatible with monolithic microwave integrated circuits. The nitride film is deposited by electron cyclotron resonance—chemical vapor deposition directly over GaAs-*n* substrate and over InGaP/GaAs heterojunction structures, which are used for heterojunction bipolar transistors (HBTs). Metal/nitride/GaAs-*n* capacitors were fabricated for all the samples. Effective charge densities of 3×10^{11} cm^{-2} and leakage current densities of 1 μA/cm^2 were determined. Plasma analysis showed a reduced formation of molecules such as NH in the gas phase at low pressures, allowing the deposition of higher quality films. The process was used for InGaP/GaAs HBT fabrication with excellent results, such as higher current gain of passivated device comparing to unpassivated HBTs. [DOI: 10.1116/1.2209998]

I. INTRODUCTION

With the reduction in dimensions of high frequency devices, it is of critical importance that leakage currents be kept at a minimum. In particular, in compound semiconductor devices, such as heterojunction bipolar transistors (HBTs) and modulation-doped field effect transistors (MODFETs), high surface charge density produces a high recombination velocity, which severely limits device performance.[1] Although GaAs has excellent mobility characteristics, which translates into faster circuits, the poor surface quality has prevented its larger scale utilization, as opposed to Si. Also, the development of good-quality metal-insulator-semiconductor (MIS) structures on GaAs has been hampered due to the lack of a suitable insulator.[2] Usually, this problem is dealt with using the surface passivation through deposition of a thin nitride film. This process requires prior surface treatment of N_2 and/or H_2 and/or NH_3 plasmas in order to remove native oxide and fill the surface dangling bonds,[3–6] forming an ultrathin GaN layer. Moreover, the nitride film is frequently deposited on a thin layer of Si over GaAs in order to take advantage of the well-behaved Si oxides.[7] Furthermore, SiH_4 and NH_3 and/or N_2 gas sources, which have been used in electron cyclotron resonance-chemical vapor deposition (ECR-CVD) plasma reactors to obtain the silicon nitride passivation layer, can degrade the III-V semiconductor surfaces due to enhanced ion bombardment and hydrogen incorporation at HBT emitter and base areas or substrates.[3,4,8,9]

In this work, we present a one-step passivation process by ECR-CVD deposition which requires no pretreatment (such as, H_2 and N_2 plasma surface pretreatment),[5,6] is fully compatible to monolithic microwave integrated circuits (MMICs), and does not require any changes in the lithographic process. The silicon nitride film is deposited by ECR-CVD directly over GaAs and over InGaP/GaAs heterojunction structures, which are used for HBTs. Optical emission spectrometry (OES) and a Langmuir probe were used for plasma characterization. The process is summarized in the next section. More details about silicon nitride deposition and characterization can be seen in Refs. 1, 10, and 11. Finally, we investigate the application of the insulator on a MIS structure, where *C-V* as well as *I-V* data are discussed, and to our HBT fabrication process with excellent results.

II. EXPERIMENTAL PROCEDURE

The silicon nitride layers were formed on *n*-type GaAs (100) wafers (Si doping of 1×10^{17} cm^{-3}). The substrates were cleaned with organic solvents using a Sox-let distillate. Based on previously established conditions by Diniz *et al.*,[10,11] the ECR depositions were carried out at a fixed substrate temperature of 20 °C, SiH_4/N_2 flow ratio of 1, Ar flow of 5 SCCM (SCCM denotes cubic centimenter per minute at STP), pressure of 2 mTorr and microwave (2.45 GHz) and rf (13.56 MHz) powers of 250 and 4 W, respectively.

Metal/nitride/GaAs capacitors were fabricated from all the samples considered with 285-nm-thick AuGeNi gate and wafer backside electrodes, which were formed by e-beam evaporation, sintered by conventional furnace in forming gas ($92\%N_2+8\%H_2$) at 450 °C for 3.5 min. The electrodes were patterned with a mask composed of an array of 200 μm-diam. dots. *C-V* measurements at 1 MHz were performed. The effective charge densities Q_0/q were calculated directly from the flatband voltage shift V_{fb} and C_{max}. All measurements were carried out at room temperature. Leakage current densities are determined through *I-V* characterization.

Two types of HBTs were developed for this study, a passivated structure [Fig. 1(a)] and an unpassivated structure.

[a]Electronic mail: daltrini@led.unicamp.br

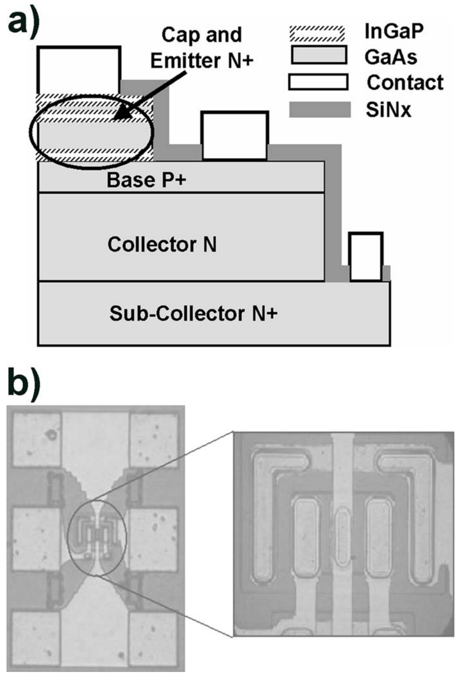

FIG. 1. Passivated structure: silicon nitride film (as passivation layer) deposited on the InGaP/GaAs HBTs devices by ECR plasma processing. (a) HBT structure layer. (b) HBT top side view with 20×6 μm^2 emitter area.

The detailed composition of each layer is shown in Table I. The fabrication process is very similar to the one described for AlGaAs/GaAs HBTs in Ref. 1 except that before the interconnection isolation process a 60 nm silicon nitride layer was deposited over the whole device. The nitride processed without H_2 and N_2 plasma surface pretreatment was employed. Then, via holes are opened by plasma etching. The final structure is depicted in Fig. 1(a) and a top side view optical micrography in Fig. 1(b). The generated transistors had 20×6 and 20×16 μm^2 emitter area sizes and all HBTs studied are nonself aligned structures. Comparisons between passivated and unpassivated transistors were performed.

III. RESULTS AND DISCUSSIONS

Fourier transform infrared (FTIR) spectrometric and ellipsometric results of similar deposited silicon nitride films for AlGaAs/GaAs surface passivation are reported by Diniz *et al.*[10,11] These films present a 1.9 refractive index, which indicates nitrogen rich films, with low H incorporation. The N–H concentration presented was lower than 1×10^{22} cm^{-3}. Furthermore, the Si–H bond absence in the deposited films gives clear evidence of the formation of low-stress films with reduced hydrogen content.[12]

TABLE I. Detailed HBT structure.

Layer	Material	Thickness (nm)	Doping (cm^{-3})
Cap	$In_yGa_{1-y}As$ ($y=0.5$)	50	$>1.0 \times 10^{19}(n^+)$
Cap	$In_yGa_{1-y}As$ ($y=0-0.5$)	50	$>1.0 \times 10^{19}(n^+)$
Cap	GaAs (Si)	100	$5.0 \times 10^{18}(n^+)$
Emitter	$In_yGa_{1-y}P$ ($y=0.5$) (Si)	50	5.0×10^{17} (n)
Base	GaAs (C)	80	$4.0 \times 10^{19}(p^+)$
Collector	GaAs (Si)	500	4.0×10^{16} (n)
Subcollector	GaAs (Si)	500	$5.0 \times 10^{18}(n^+)$

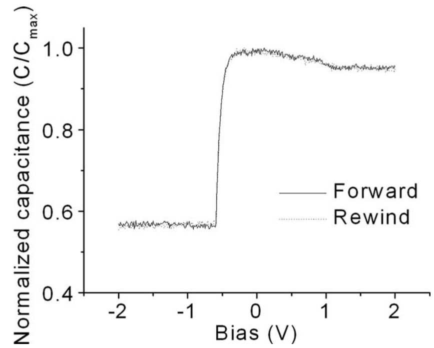

FIG. 2. *C-V* curves of the capacitors.

The *C-V* characteristics of capacitors with nitride were investigated. Figure 2 shows *C-V* plots for the samples. The average effective charge density Q_0/q, was found to be about 3×10^{11} cm^{-2} (calculated directly from the flatband voltage shift V_{fb}). Furthermore, the *C-V* characteristics for nitride films showed no hysteresis and no distortion, indicating low interface state density, and therefore, an excellent GaAs surface passivation. The *I-V* characteristic was taken to verify the leakage current densities. Figure 3 shows the leakage current densities lower than 1 $\mu A/cm^2$ (between −2 and 2 V) indicating a low leakage current.

These electrical properties indicate that the formed silicon nitride films have presented high quality, very low effective charge density, comparable to nitrides deposited on silicon,[5,7,10] and excellent GaAs surface passivation results.

The passivation of GaAs surface during the ECR-CVD nitride deposition occurs as follows. In the process beginning, hydrogen and nitrogen atoms and ions generated in the high-density ECR plasma remove a native oxide at the GaAs substrate surface and form an ultrathin GaN layer. It is important that the degree of dissociation of SiH_4 and N_2 molecules here is much higher compared with conventional plasma enhanced CVD. Previous studies have shown that the

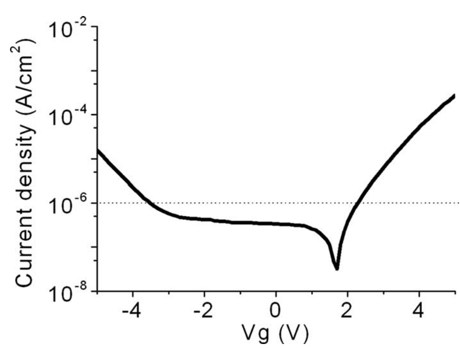

FIG. 3. *I-V* curve of the capacitors.

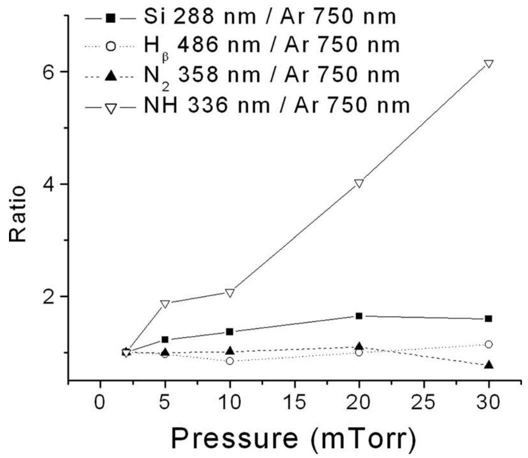

FIG. 4. Line emission ratios for ECR plasma silicon nitride depositions vs gas pressure.

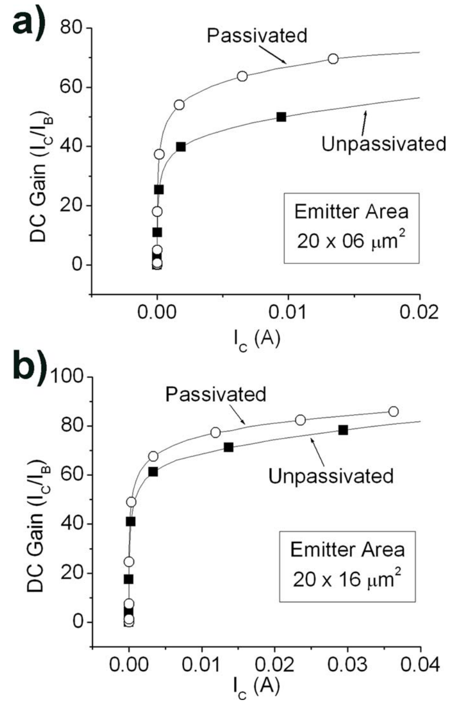

FIG. 5. dc gain plot for passivated and unpassivated HBT. Emitter areas are (a) 20×6 μm^2 and (b) 20×16 μm^2.

SiH_4/N_2 flow ratio should be close to 1, otherwise either the native oxide removal is blocked (at the excess of nitrogen in the oxide surface layer) or the nitride film is not formed (at the excess of hydrogen).[3,4,7] Furthermore, the microwave power and pressure should be kept at relatively low levels of 250 W and 2 mTorr, in order to avoid excessive dissociation of silane and generation of secondary products in the gas phase. This makes possible a soft removal of the native oxide followed by the surface nitridation and deposition of a high quality SiN_x film (see below).

The ECR plasma was characterized by OES in a 200–900 nm spectral range. Figure 4 presents some spectral emissions (Si 288 nm, H_β 486 nm, N_2 358 nm, and NH 336 nm), normalized by the Ar 750 nm emission, as a function of pressure. It can be seen that while the N_2 and hydrogen relative intensities change only slightly with pressure, the Si and especially the NH emission clearly increase with pressure. This is explained by higher dissociation of gas molecules and stronger generation of radicals (such as NH) in gas phase reactions as the pressure rises. Note that NH radicals can contribute to formation of porous nitride films and thus are not desirable. Langmuir probe measurements in similar neat Ar plasmas show that the electron temperature is maximum at low pressures, and the electron density is peaked between 10 and 20 mTorr. Therefore, the lowest pressure used here (2 mTorr) favors an efficient generation of atomic H and N (and, probably, their ions) together with SiH_3 radicals rather than highly unsaturated SiH_x $(x<2)$ radicals, which are known to have high sticking coefficient and low surface mobility and thus contribute to production of porous nitride films.

Furthermore, high pressure processing can degrade the III-V semiconductor surfaces (such as GaAs substrates and AlGaAs/GaAs or InGaAs/InP HBT structures), due to preferential losses of As or P. This effect should be enhanced by ion bombardment, so that operation at higher plasma densities (high power and pressure) should be avoided in order to reduce the ion bombardment. Another problem of depositions at higher pressures is the hydrogen incorporation at HBT emitter and base areas or substrates.[3,4,8,9]

The dc gain plots for the InGaP/GaAs HBTs (passivated and unpassivated transistors) are shown in Fig. 5. The devices have emitter areas of 20×6 and 20×16 μm^2, and passivated HBTs presented high dc gain than unpassivated devices (with difference higher than 10). Thus, the benefit of the passivation is striking. In the unpassivated devices surface states represent an escape route for carriers being injected from the emitter. Such carriers recombine at these states without contributing to the collector current.

The base current is composed of four main contributions, namely, the recombination current at the base-emitter space-charge region J_{Bsc}, the bulk recombination current J_{bulk}, the back-injection current (holes from base to emitter) J_{bp}, and the surface recombination current J_{surf}. In the HBT J_{bp} can, generally, be neglected due to the heterojunction barrier. Moreover, for abrupt devices the recombination current in the base bulk region is larger than in the space-charge region.[1] In order to quantify the effect one notes that[1]

$$\frac{J_C}{\beta} = (J_{bulk} + J_{Bsc}) + 2K_{surf}\left(\frac{1}{W_E} + \frac{1}{L_E}\right), \qquad (1)$$

where β is the transistor current gain, K_{surf} is the surface recombination current divided by the emitter periphery and W_E and L_E are the emitter dimensions. By plotting J_C/β vs $(1/W_E+1/L_E)$ it is straightforward to obtain the contribution of the surface recombination current. This is shown in Fig. 6. One can observe a lower angular coefficient for the passivated device, which is the result of a lower surface recombination current.

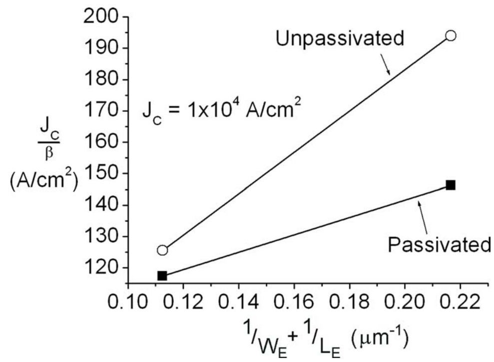

FIG. 6. Variation of J_C/β with $(1/W_E+1/L_E)$ for passivated and unpassivated HBTs. The data was obtained at a collector current density of 1×10^4 A/cm^2.

IV. CONCLUSIONS

A passivation technique was described in which a silicon nitride film is deposited by ECR-CVD directly over the target GaAs layer. The procedure requires no pretreatment of the surface and is compatible with integrated circuit technology.

For the plasma characterization, an optical emission spectrometry and a Langmuir probe were used. It has been shown that the lowest pressure used here (2 mTorr) favors an efficient generation of atomic H and N together with SiH_3 radicals rather than highly unsaturated SiH_x $(x\leq 2)$ radicals, which are known to produce porous nitride films. Furthermore, at low pressures the formation of molecules such as NH in the gas phase is reduced. As a result, higher quality films are produced at a low pressure and reduced ECR power of 250 W. High pressure processing also can lead to a degradation of the III-V semiconductor surfaces due to preferential losses of As or P and the hydrogen incorporation at substrate.

Metal/nitride/GaAs-*n* capacitors were fabricated from all the samples considered with 285-nm-thick AuGeNi gate and wafer backside electrodes. The gate electrodes were patterned with a mask composed of an array of 200-μm-diam. dots. *C-V* measurements at 1 MHz were performed. The effective charge densities Q_0/q of 3×10^{11} cm^{-2} were calculated directly from the flatband voltage shift V_{fb}. Leakage current densities of 1 μA/cm^2 (between −2 and 2 V) were determined through *I-V* characterization. We have applied this film to the InGaP/GaAs HBT fabrication process with excellent results, such as higher current gain of passivated device comparing to unpassivated HBTs. Furthermore, the silicon nitride was deposited over InGaP/GaAs HBT structures and the results from transistor characterization demonstrated the efficacy of the process. A comprehensive study of the device's current was conducted, whereby it was determined that surface recombination current plays a critical role in device performance. A current gain enhancement for the entire measured range of collector current (compared with unpassivated HBT) was observed. This feature is of great value in the design of low noise, low power consumption and high quality circuits, a key point in today's telecommunication industry.

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