ARTICLE IN PRESS

Materials Science in Semiconductor Processing xxx (xxxx) xxx–xxx

Contents lists available at ScienceDirect

Materials Science in Semiconductor Processing

journal homepage: www.elsevier.com/locate/mssp

Review of technology for normally-off HEMTs with p-GaN gate

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ARTICLE INFO

Keywords:
Normally-off HEMT
P-GaN
AlGaN/GaN heterostructures

ABSTRACT

Owing to the high carrier density and high electron mobility of the two dimensional electron gas (2DEG), high electron mobility transistors (HEMTs) based on gallium nitride (GaN) are suitable devices for high power and high frequency applications. Clearly, the presence of the 2DEG at the interface of AlGaN/GaN heterostructures makes HEMTs intrinsically normally-on devices. However, for power electronics applications, normally-off operation is desired for safety reasons and to simplify the driver circuitry. In this context, although several approaches to obtain normally-off transistors have been reported in the literature, normally-off GaN-based HEMTs with a p-GaN gate is among the most promising and the only commercially available today.

This paper reviews the most relevant technological issues for normally-off HEMTs with a p-GaN gate. First the operation principle and the impact of the heterostructure parameters are discussed. Then, the possible effects of the dry etching process of p-GaN are shortly mentioned. Thereafter, the role of the metal/p-GaN interface and the impact of the thermal processes on the electrical characteristics are widely discussed. Finally, recent alternative approaches proposed to avoid the use of the p-GaN dry etching are presented.

1. Introduction

Gallium Nitride (GaN) and related semiconducting alloys (like AlGaN, InGaN, …) have been repeatedly mentioned as promising materials for the next generation of high-power and high-frequency electronics device [1–3]. In particular, High Electron Mobility Transistors (HEMTs) based on AlGaN/GaN heterostructures have superior performances with respect to their silicon (Si) counterparts, as they can operate at higher voltage, higher current, higher frequency and higher temperature [4], owing to the high electric field strength of the material combined with the high mobility and electron density of the two dimensional electron gas (2DEG) formed at the AlGaN/GaN interface [5].

Besides these intrinsic advantages, there is also a great interest in the possibility to grow AlGaN/GaN heterostructures on low-cost large-area (up to 200 mm) Si substrates, due to the enormous market potential and the possibility to integrate GaN power switches with the consolidated Si CMOS circuit technology [6]. Consequently, over the last decade, great efforts have been made to optimize the trade-off between the breakdown voltage (B_V) and specific ON-resistance (R_{ON}) of nitride-based transistors, e.g., working on the device geometry, reducing the defect density in the material and buffer layers, and developing new processing solutions for devices fabrication [7].

While normally-on AlGaN/GaN HEMTs are used for low-voltage and high frequency applications, for power switching applications normally-off characteristics are required to guarantee a safe operation and a simple gate drive configuration [8,9].

Several approaches have been proposed in order to obtain normally-off GaN-based HEMTs. In principle, the 2DEG depletion can be achieved using a thin AlGaN barrier layer with a low Al concentration. However, for an optimal device operation in terms of R_{ON}, the depletion of the 2DEG channel must be localized only below the gate, and it should be possible to completely restore the sheet carrier density through the application of a positive gate bias. Hence, the first practical solution proposed for normally-off GaN HEMT has been the recession of the AlGaN barrier layer in the region below the gate electrode, by local plasma etch process [10]. Obviously, this approach requires an accurate control of the AlGaN etching technology. Moreover, the damage induced by the etching process could lead to an increase in the gate leakage current and to threshold voltage (V_{th}) non-uniformity effects. Hence, to improve the V_{th} uniformity and obtaining a low R_{ON}, a novel piezoneutralization technique has been proposed, which is based on the partial recession of a barrier layer composed by several AlGaN layers with different Al concentration [11].

On the other hand, the introduction of fluorine below the gate electrode has been also used to obtain normally-off operation. In this case, the negative charge of the F-ions, introduced either by plasma etch [12,13] or ion-implantation [14], promotes the depletion of the 2DEG channel, thus leading to a positive shift of threshold voltage V_{th}

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http://dx.doi.org/10.1016/j.mssp.2017.09.027
Received 6 July 2017; Received in revised form 12 September 2017; Accepted 25 September 2017

Please cite this article as: Greco, G., Materials Science in Semiconductor Processing (2017), http://dx.doi.org/10.1016/j.mssp.2017.09.027

of the transistor. However, the V_{th} stability after high temperature annealing can be a concern in this kind of device [15].

Alternative but less diffused approaches to obtain a positive V_{th} shift include the local surface oxidation processes [16–18] or the introduction of a NiOx-based interlayer below the gate [19–21].

To overcome many of the above limitations, the hybrid MIS-HEMT configuration has been proposed [22]. In this device, the AlGaN barrier layer is completely removed below the gate, forming the channel using a MIS system. Hence, this approach combines the advantages of a normally-off MIS channel with the low resistance of the 2DEG. However, the choice of the dielectric layer is extremely important in GaN devices [23,24], and in MISHEMTs it specifically impacts both the channel mobility [25,26] and threshold voltage stability [27].

Probably, the most promising approach is the use of a p-GaN (or p-AlGaN) layer on the AlGaN/GaN heterostructure under the gate contact region [28,29]. In this case, the p-GaN layer lifts up the band diagram, resulting in the depletion of the 2DEG channel even in the absence of an external applied bias ($V_G = 0$). This process is receiving a great attention within the scientific community and, as a matter of fact, the only "real" normally-off GaN HEMT commercially available to date are based on a p-GaN gate. Clearly, the technology of normally-off HEMT with p-GaN is rather complex, and the device behavior can be significantly influenced by several layout and processing conditions, which will be discussed in the present paper (e.g., choice of the heterostructure, selective p-GaN etch process, gate contacts, thermal budget, etc.). Obviously, there are other important reliability aspects associated to the normally-off AlGaN/GaN HEMT technology with a p-GaN gate, such as threshold voltage stability [30,34], charge trapping mechanisms [31], degradation processes induced by positive gate bias [30,32,33] or induced by high drain bias in off-state [34]. All these aspects are not treated in the present work as they have been widely discussed in another recently published review paper [34].

In this paper, the main technological issues related to the fabrication of normally-off HEMTs with p-GaN gate are reviewed. In particular, in Section 2.1 after an introduction on the operation principle of the normally-off HEMT with p-GaN, the importance of the p-GaN/AlGaN/GaN heterostructure parameters (thickness, Al molar fraction, etc.) are discussed. Then, in Section 2.2, the possible issues related to the selective plasma etch of the p-GaN are briefly illustrated. Thereafter, in Section 2.3 the impact of the metal gate on the electrical behavior of the normally-off p-GaN HEMTs is widely discussed. In particular, the choice metal gate work function and the p-GaN doping concentration, as well as the impact of the thermal annealing processes on the metal/p-GaN barrier are discussed, with a focus on the case study of a Ti/Al gate. Finally, in Section 3 some recent alternative approaches to achieve normally-off p-GaN HEMTs without using of p-GaN dry etching are briefly mentioned.

2. Technological issues for normally-off HEMTs with p-GaN

2.1. Operation principle and impact of the heterostructure properties

The operation principle of the normally-off HEMT using a p-GaN gate is schematically depicted in Fig. 1. Basically, the use of a standard Schottky contact as gate electrode onto an AlGaN/GaN heterostructure leads to normally-on operation of the devices, as the AlGaN conduction band edge lies bellow the Fermi level at the interface with GaN. On the other hand, after the introduction of a p-GaN cap layer onto the AlGaN, the conduction band of the AlGaN is lifted up, thus leading to the depletion of the 2DEG. In this way, in principle, the normally-off operation of the device can be achieved.

However addition of any p-GaN capping layer on top of an AlGaN/GaN heterostructure not necessarily ensure normally-off operation. In fact, an appropriate choice of all the heterostructure parameters (i.e., acceptor concentration of p-GaN, residual donor concentrations in the AlGaN and GaN, thickness (d_{AlGaN}) and Al molar fraction (x_{AlGaN}) of the $Al_xGa_{1-x}N$ barrier layer, etc.) is fundamental in order to efficiently deplete the 2DEG channel and achieve a reasonable threshold voltage V_{th}.

First of all, to facilitate the 2DEG depletion in the equilibrium condition (at $V_G = 0$), a high acceptor concentration of the p-type GaN cap layer must be used. However, while an intrinsic n-type conductivity is typically observed even in nominally undoped GaN or AlGaN [35], the achievement of a p-type conductivity in GaN has been a long standing problem [36]. Magnesium (Mg) is the reference p-type dopant for GaN or AlGaN, as it acts as an acceptor when incorporated in the nitride lattice in substitution of Ga. However, it is difficult to obtain a high holes concentration in p-GaN (or p-AlGaN), since the ionization energy of Mg p-type dopant is relatively high, i.e., in the range 150–200 meV [37,38]. Typically, p-type GaN cap layers with an acceptor concentration of about $3 \times 10^{19}\,cm^{-3}$ are used, i.e., around three orders of magnitude higher than the residual donor doping concentration of the AlGaN layer. A higher Mg content in the p-GaN is not recommended, since its incorporation could lead to a deterioration of the crystalline quality of the layer and to a consequent decrease in the electrically active acceptors [39].

The thickness (d_{AlGaN}) and the Al molar fraction (x_{AlGaN}) of the $Al_xGa_{1-x}N$ barrier layer are two important parameters influencing the band diagram of the p-GaN/AlGaN/GaN heterostructure and, hence, the overall electrical behavior of the system. Fig. 2a shows the simulated conduction band in the case of a p-GaN/AlGaN/GaN heterostructure, with an AlGaN thickness $d_{AlGaN} = 25$ nm and two different Al concentration values, i.e., $x_{AlGaN} = 0.12$ and $x_{AlGaN} = 0.26$ (a). A one-dimension Poisson-Schrödinger solver has been used to determine the energy band diagram. In particular, the thickness of the p-GaN layer was 50 nm and its acceptor concentration was $N_A = 3 \times 10^{19}\,cm^{-3}$. As can be observed, in case of a higher Al molar fraction, the only presence of p-GaN is not sufficient to achieve a normally-off behavior in the equilibrium condition (at $V_G = 0$ V), as the conduction band edge at the AlGaN/GaN interface lies still below the Fermi level. On the other hand, using a lower Al molar fraction of the barrier layer ($x_{AlGaN} = 0.12$) enables a more efficient depletion of the 2DEG (as the conduction band edge lies now well above the Fermi level), leading to a heterostructure suitable for normally-off operation. A similar behavior can be observed in Fig. 2b, which reports the conduction band diagram of the p-GaN/AlGaN/GaN heterostructure with an Al molar fraction of $x_{AlGaN} = 0.26$, for two different AlGaN thickness values ($d_{AlGaN} = 10$ nm and $d_{AlGaN} = 25$ nm). In this case, a complete depletion of the 2DEG can be achieved only in the heterostructures with the thinner AlGaN barrier layer (10 nm). In this context, Fujii *et al.* [40] simulated the band diagram of p-GaN/AlGaN/GaN heterostructures by varying both the AlGaN thickness (d_{AlGaN}) and the Al molar fraction (x_{AlGaN}). In this way, it was possible to draw a "borderline" between heterostructures suitable for normally-off or normally-on operation, as can be seen in the plot reported in Fig. 2c. The separation line between the two operation conditions has been calculated considering the intersection point of the bottom of the conduction band with the Fermi level, in a d_{AlGaN} vs x_{AlGaN} graph. In the same graph, the symbols indicate the conditions simulated in Fig. 2a and b.

Following the first pioneering work by Hu et al. [41], a huge step forward in the technology of normally-off HEMTs with p-GaN gate was recorded in 2007 by Uemoto et al. [28], who demonstrated a normally-off device using a p-type AlGaN gate. In that work, they observed an interesting effect in the transfer characteristics of the devices, due to the injection of holes towards the interface, which give to the devices the name of Gate Injection Transistor (GIT).

Fig. 3 reports the transfer characteristics I_{DS}-V_G and the transconductance g_m of the GIT devices (Fig. 3a) as well as a schematic of the device structure explaining the principle of operation (Fig. 3b). From the transfer characteristics, a positive threshold voltage V_{th} of about 1.0 V can be estimated. Interestingly, two different peaks, at two different gate voltages, can be observed in the g_m curve. A schematic cross