Growth and properties of GaN and AlN layers on silver substrates

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We report on the preparation and properties of GaN and AlN layers grown by molecular-beam epitaxy on silver metal substrates. X-ray diffraction rocking curves show polycrystalline character of GaN with high preferential GaN(11-22) orientation. An intermetallic phase of Ga_3Ag is found at the GaN/Ag interface. On the other hand, AlN layers exhibit a monocrystalline structure with a growth direction of (0002). Schottky diodes prepared on GaN layers show good rectifying behavior and relatively low leakage current ($\sim 10^{-3}$ A/cm^2). These results indicate that the III-nitride growth on metallic substrates might be used for low-cost and large-area electronic and photonic devices. © *2005 American Institute of Physics*. [DOI: 10.1063/1.2135879]

The growth and deposition of semiconductor thin films on metallic substrates has been well known for about three decades. Properties of silicon layers deposited onto tungsten and nickel substrates,[1] as well as on steel,[2] have been published. Gallium arsenide[3] grown by liquid phase epitaxy on a polycrystalline Mo metal substrate with a grain size sufficient for high efficiency solar cells has been reported in the past. Since the GaN layers were grown by plasma-assisted molecular beam epitaxy (MBE),[4] the photoluminescence properties of polycrystalline GaN grown on W, Mo, Ta, and Nb metal substrates by MBE were intensively studied in last decade.[5–7] The underlying reason for semiconductor growth on metal substrates might be good thermal conductivity to the environment or low-cost solutions for large-area circuits.

The aim of our work is the growth of monocrystalline GaN and AlN on a silver metal substrate. We describe the growth process of the epitaxial layers that are characterized by x-ray diffraction (XRD) measurements. Schottky diodes on a GaN layer with AlN as a nucleation layer demonstrate the ability to fabricate GaN-based devices on a metal substrate.

The III-N layers were grown by MBE using standard effusion cells and a radio-frequency (rf)-plasma source operating at 13.56 MHz, rf power of 450 W, and 1 sccm nitrogen flux. The chamber pressure during the growth was 1×10^{-5} mbar. In a first series, GaN was grown directly on a silver substrate with a substrate temperature of 760 °C. The Ga beam equivalent pressure (BEP) was varied from 2.5×10^{-7} to 5×10^{-7} mbar for different runs. The thickness of the layers is around 500 nm. In a second series, a low-temperature AlN nucleation layer with a substrate temperature of 600 °C was grown on the silver substrate. The BEP of the Al cell was changed from 1.0×10^{-7} to 1.4×10^{-7} mbar for different runs. The thickness of this layer was approximately 100 nm. Subsequently, a GaN layer was grown on top of the AlN layer at a substrate temperature of 760 °C. The thicknesses of the investigated layers were measured with a surface profilometer (Dektak), the surface morphology was characterized using atomic force microscopy (AFM), and the structural properties were determined with XRD.

Figure 1 shows the XRD pattern of a GaN layer grown directly on the silver substrate. We observed a polycrystalline character of the GaN layer with highly preferential GaN(11-22) reflexes. Furthermore, additional diffraction peaks of GaN(10-11) and GaN(10-14) were seen. At the interface of the substrate and the grown layer, an intermetallic phase of Ag_3Ga was formed, as is derived from the corresponding diffraction peaks. Figure 2 shows the XRD spectrum of an AlN layer grown on a silver substrate. In spite of the polycrystalline substrate, the grown AlN layer shows monocrystalline equilibrium wurtzite structure with a growth direction (0002). No intermetallic phases were observed at the interface at the lower substrate temperature. For the GaN growth on Ag, however, it is energetically more favorable to form Ag–Ga clusters at the interface, probably due to the higher substrate temperature of 760 °C compared to 600 °C for the AlN epitaxy. Figure 3 displays an AFM picture of the surface morphology of the GaN layer with AlN nucleation layer

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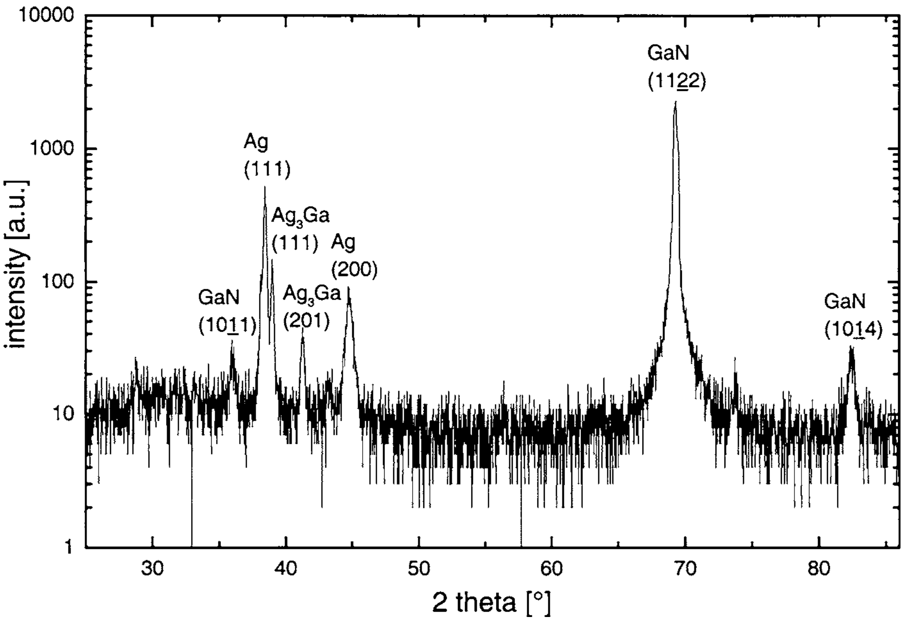

FIG. 1. XRD spectrum of a GaN layer grown on silver substrate. The Ga BEP is 2.5×10^{-7} mbar. Diffraction peaks for different GaN orientations (11–22), (10–11), and (10–14) can be identified.

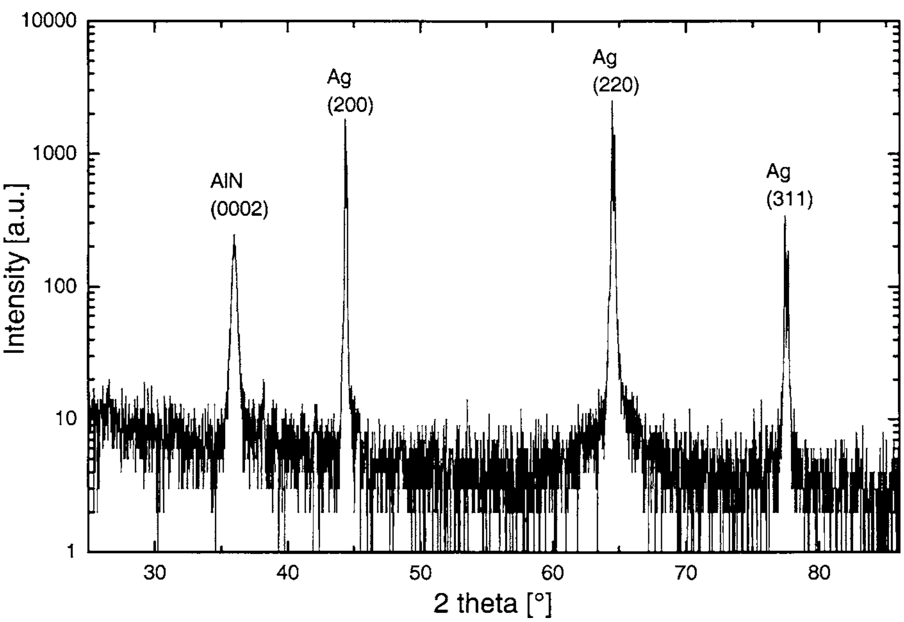

FIG. 2. XRD spectrum of an AlN layer grown on silver substrate. The Al BEP is 1.0×10^{-7} mbar. Only one single AlN peak is observed.

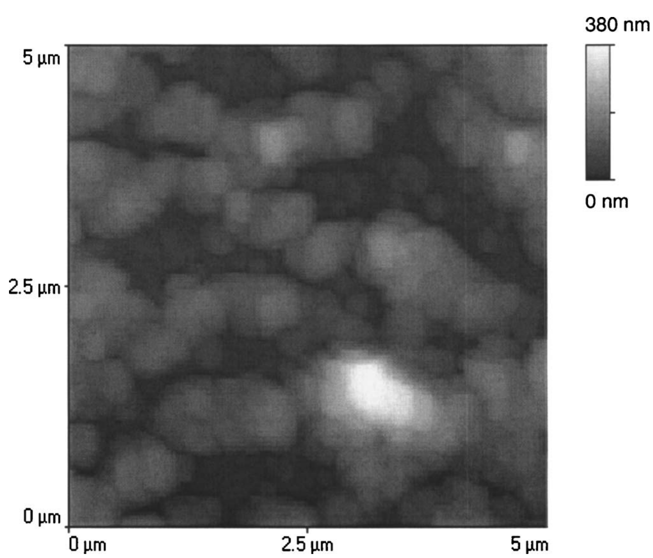

FIG. 3. Surface morphology of a GaN layer grown on AlN/Ag measured by AFM.

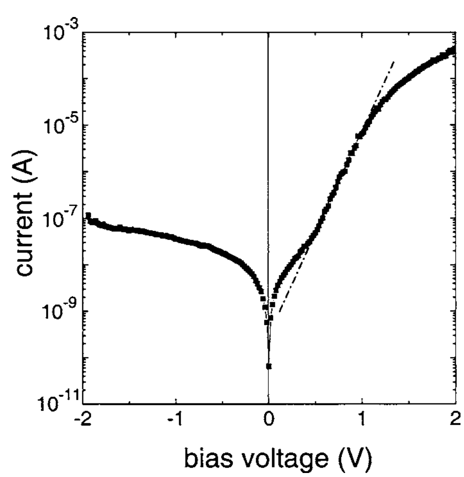

FIG. 4. *I-V* characteristic measured in the dark of a diode with an area of 2500 μm^2 fabricated on Ag/AlN/GaN material.

grown on silver substrate. The BEP was 2.5×10^{-7} mbar and 1.0×10^{-7} mbar for Ga and Al, respectively. The surface exhibits oval-shaped grains with nearly uniform size. The root-mean square of the surface roughness is about 56 nm for 5×5 μm^2 area. The high value is probably affected by the polycrystalline character of the metallic substrate with a surface roughness of about 50 nm, measured with a profilometer.

Planar Schottky diodes were fabricated on this layer system. The ohmic contact consists of a Ti/Al/Ni/Au multilayer and was deposited onto the wet chemically cleaned oxide-free GaN surface. The ohmic behavior was achieved by annealing for 30 s at 800 °C in a nitrogen ambient. The Schottky contact was created by a Ni/Au metal layer which was deposited directly after a HF dip. The diode characteristics were measured on circular-shaped structures, where the ohmic contact completely surrounds the Schottky electrode. The current-voltage (I-V) curve (Fig. 4) shows a typical diode characteristic with ohmic series resistance. The device exhibits an ideality factor of about 3.6. The saturation current reaches a value of about 2×10^{-10} A for a device area of 2500 μm^2. The slight increase of the reverse current at −2 V shown in the I-V curve can be related to the imperfect quality of the grown layer. More work has to be done in order to improve of the quality of GaN epitaxial films grown on a Ag substrate.

In conclusion, we have grown III-N layers by MBE on a polycrystalline silver substrate. XRD measurements show the polycrystalline character of the GaN layers and the monocrystalline character of low-temperature AlN grown directly on the metallic substrate. Schottky diodes on GaN grown on a silver substrate with an AlN nucleation layer exhibit as low as 2×10^{-10} A saturation current and an ideality factor of 3.6. These results show that with further optimization of GaN grown on metal substrates, this material system is a very promising candidate for large-scale applications in the semiconductor industry.

[1] G. W. Racette and R. T. Frost, J. Cryst. Growth **47**, 384 (1979).

[2] D. E. Carlson, *Proceedings of the Third E.C. Photovoltaic Solar Energy Conference* (Reidel, Dordrecht, The Netherlands, 1981), p. 294.

[3] J. M. Woodall, IBM Tech. Discl. Bull. **21**, 2584 (1978).

[4] R. Beresford, K. S. Stevens, C. Briant, R. Bai, and D. C. Paine, Mater. Res. Soc. Symp. Proc. 55 (1996).

[5] K. Yamada, H. Asahi, H. Tampo, Y. Imanishi, K. Ohnishi, and K. Asami, *Proceedings of International Workshop on Nitride Semiconductors* (Inst. Pure & Appl. Phys, Tokyo, Japan, 2000), p. 556.

[6] K. Yamada, H. Asahi, H. Tampo, and Y. Imanishi, Appl. Phys. Lett. **78**, 2849 (2001).

[7] A. V. Andrianov, K. Yamada, H. Tampo, and H. Asahi, Semiconductors **36**, 878 (2002).