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HIGH-DENSITY PLASMA ETCHING OF GROUP-III NITRIDE FILMS FOR DEVICE APPLICATION

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As III-V nitride device structures become more complicated and design rules shrink, well-controlled etch processes are necessary. Due to limited wet chemical etch results for the group-III nitrides, a significant amount of effort has been devoted to the development of dry etch processing. Dry etch development was initially focused on mesa structures where high etch rates, anisotropic profiles, smooth sidewalls, and equi-rate etching of dissimilar materials were required. For example, commercially available LEDs and laser facets for GaN-based laser diodes have been patterned using reactive ion etching (RIE). With the recent interest in high power, high temperature electronic devices, etch characteristics may also require smooth surface morphology, low plasma-induced damage, and selective etching of one layer over another. The principal criteria for any plasma etch process is its utility in the fabrication of a device. In this study, we will report plasma etch results for the group-III nitrides and their application to device structures.

INTRODUCTION

Etch requirements are often defined independent of device structure. For example, run-to-run repeatability, uniformity across the wafer, smooth etch morphology, and dimensional control are typically necessary for any device fabrication sequence. However, due to the unrivaled success of group-III nitride LED and laser diodes, the majority of etch process development for these films has been directed toward mesa-structures where fast etch rates, anisotropic profiles, smooth etch morphology, and equi-rate etching of dissimilar materials is necessary. For many of these device structures the mesa can be several microns deep thus requiring etch rates approaching 1 μm/min. Anisotropy and smooth sidewalls are necessary to maintain critical dimensions and minimize scattering of the light. With the recent interest in high-power, high-temperature electronic devices, many of the etch requirements have changed. For example, selective etching of one material over another is very important for formation of low resistivity base ohmic contacts for heterojunction bipolar transistors (HBTs) or gate recess for high electron mobility transistors (HEMTs). In addition, etch depths are often much shallower for electronic devices, a few hundred angstroms, as compared to several microns for mesa-based devices. Furthermore, the active regions of electronic devices are often shallow thus requiring low damage induced by the plasma to ensure optimum device performance. In this study, we will report ICP etch characteristics for group-III nitride

systems (ECR and ICP) not only improve the bond-breaking efficiency, but also enhance the sputter desorption of etch products from the surface. RIBE etch rates may also have been slower as compared to ECR or ICP due to lower operational pressures (0.3 mTorr compared to 2 mTorr) or the high source-to-sample separation which reduced both the ion and neutral flux at the GaN surface.

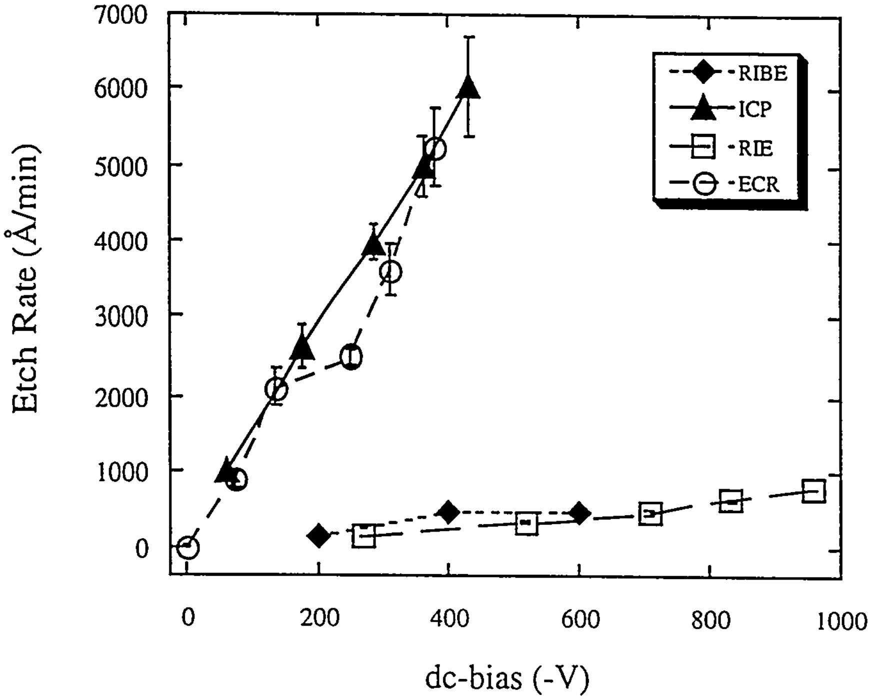


Figure 1. GaN etch rates in RIE, ECR, ICP, and RIBE Cl_2-based plasmas as a function of dc-bias. RIBE data was obtained in a Cl_2/Ar plasma whereas a $Cl_2/CH_4/H_2$/Ar plasma was used in the RIE, ECR, and ICP reactors.

Plasma Chemistry

Plasma chemistry can have a significant effect on etch rate, anisotropy, selectivity, and morphology. The fragmentation pattern and gas-phase kinetics associated with the source gas (Cl_2, BCl_3, $SiCl_4$, IBr, BBr_3, CH_4/H_2, ICl, CHF_3 etc.) can affect the concentration of reactive neutrals and ions generated in the plasma. Also the addition of secondary gases (Ar, SF_6, N_2, H_2, etc.) and variations in gas ratios can change the chemical:physical ratio of the etch mechanism.(9-15) Etch rates are often limited by the volatility of the group-III halogen etch product. Therefore, chlorine-, iodine-, and bromine-based chemistries are preferred to etch Ga- and Al-containing materials due to the high volatility of the etch product as compared to fluorine-based chemistries. Other halogen-containing plasmas, including ICl/Ar, IBr/Ar, BBr_3/Ar, and BI_3/Ar, have been used to etch GaN with promising results.(16-18) Vartuli and co-workers reported group-III nitride etch rates and selectivities in ICl/Ar and IBr/Ar plasmas.(16) Etch rates generally increased as a function of dc-bias or ion energy due to improved bond breaking and sputter desorption of etch products from the surface. GaN etch rates > 1.3 μm/min were obtained in the ICl/Ar plasma at a rf-power of 250 W (17) while GaN etch rates were typically < 4000 Å/min in IBr/Ar.(18)

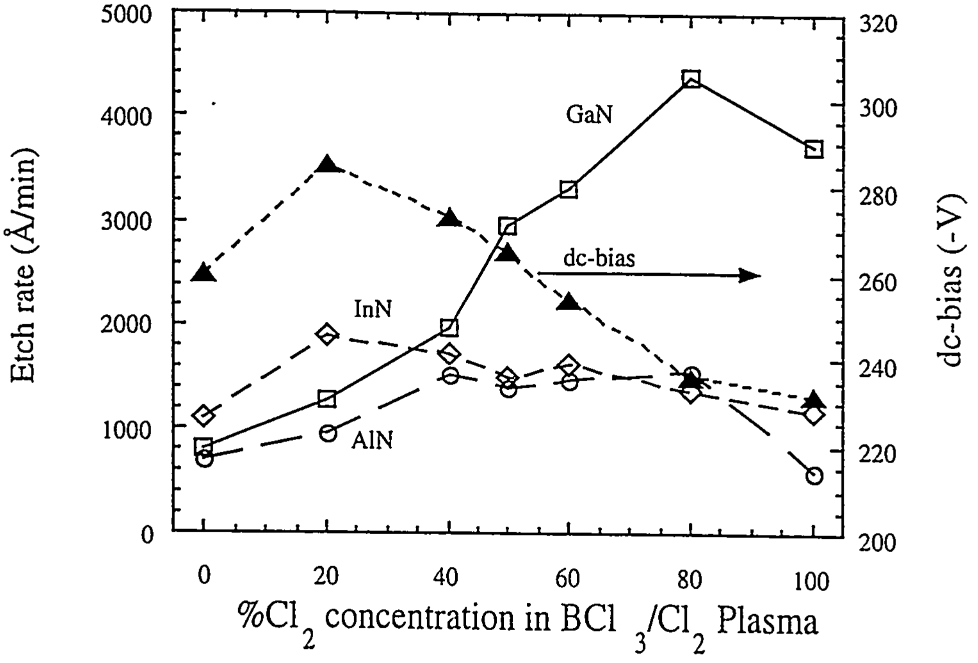


Figure 2. GaN, InN, and AlN etch rates as a function of $\%Cl_2$ in a $BCl_3/Cl_2/Ar$ ICP plasma. Plasma conditions were: 2 mTorr pressure, 500 W ICP-source power, 125 W cathode rf-power, and 25°C cathode temperature.

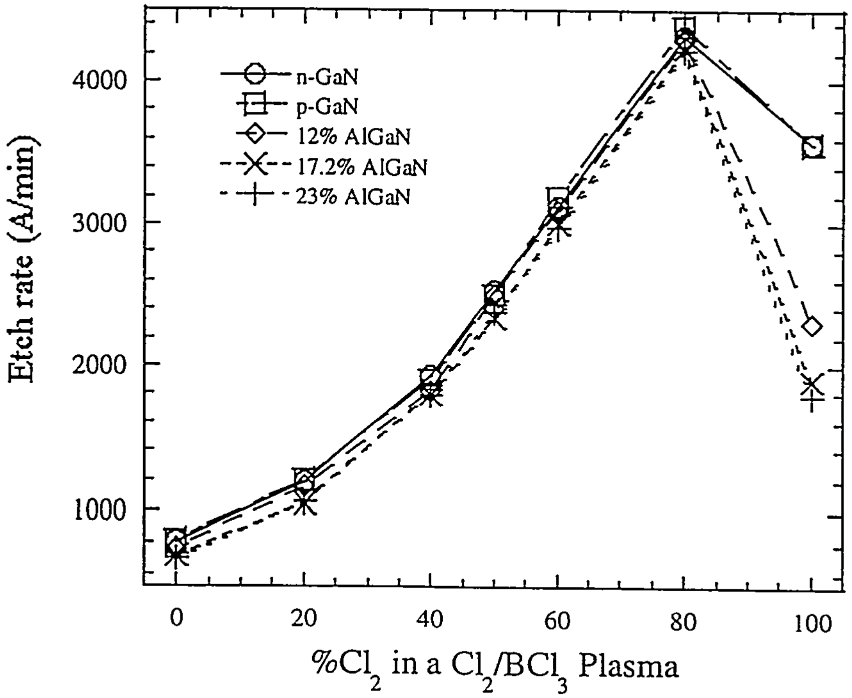


Figure 3. n-GaN, p-GaN, $Al_{0.12}Ga_{0.88}N$, $Al_{0.17}Ga_{0.83}N$, and $Al_{0.23}Ga_{0.77}N$ etch rates as a function of $\%Cl_2$ in a $BCl_3/Cl_2/Ar$ ICP plasma. Plasma conditions were: 2 mTorr pressure, 500 W ICP-source power, -150 V dc-bias, and 25°C cathode temperature.

plasma conditions were 2 mTorr pressure, -150V dc-bias, 32 sccm Cl_2, and 8 sccm BCl_3. Etch rates increased for all films up to 1000W implying either a reactant limited regime under low ICP source power, improved sputter desorption of etch products from the surface, and/or improved bond breaking under high ion flux conditions.

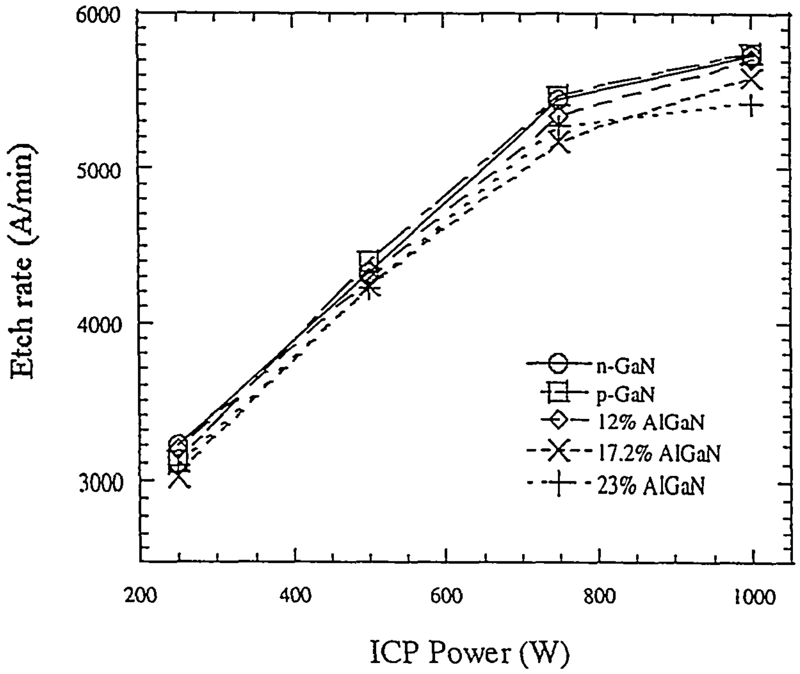
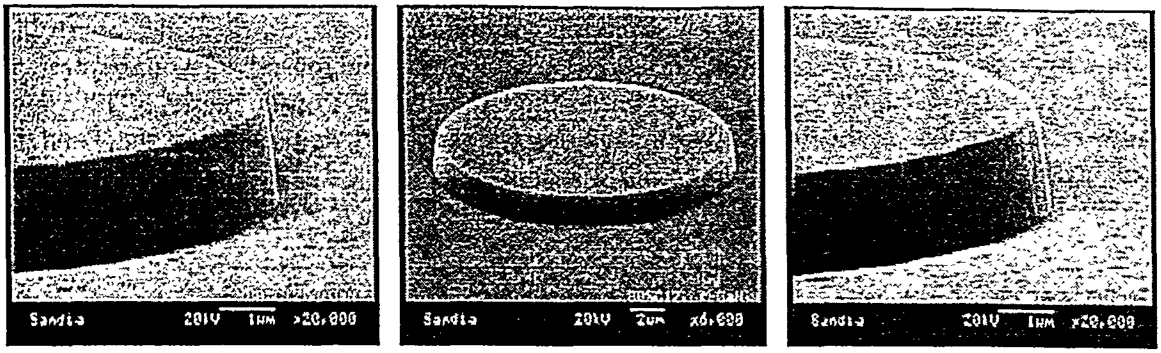


Figure 5. n-GaN, p-GaN, $Al_{0.12}Ga_{0.88}N$, $Al_{0.17}Ga_{0.83}N$, and $Al_{0.23}Ga_{0.77}N$ etch rates as a function of ICP power. Plasma conditions were: 2 mTorr pressure, 32 sccm Cl_2, 8 sccm BCl_3, 5 sccm Ar, -150 V dc-bias, and 25°C cathode temperature.

Etch Profile and Surface Morphology

Etch profile and etch surface morphology can also be critical to the fabrication of devices where anisotropic profiles are necessary or subsequent processing steps including the formation of metal contacts, deposition of interlevel dielectric or passivation films, or epitaxial regrowth require smooth surfaces. Figure 6 shows SEM micrographs of GaN, AlN, and InN etched in Cl_2-based plasmas. The GaN (Figure 6a) was etched at 5 mTorr chamber pressure, 500 W ICP power, 22.5 sccm Cl_2, 2.5 sccm H_2, 5 sccm Ar, 25°C temperature, and a dc-bias of -280 ± 10V. Under these conditions, the GaN etch rate was ~ 6880 Å/min with highly anisotropic, smooth sidewalls. The sapphire substrate was exposed during a 15% overetch. Pitting of the sapphire surface was attributed to defects in the substrate or growth process. The AlN (Figure 6b) and InN (Figure 6c) features were etched at 2 mTorr chamber pressure, 500 W ICP power, 25 sccm Cl_2, 5 sccm Ar, 25°C temperature, and a cathode rf-power of 250 W. Under these conditions, the AlN etch rate was ~ 980 Å/min and the InN etch rate was ~ 1300 Å/min. Anisotropic profiles were obtained over a wide range of plasma chemistries and conditions.



(a) (b) (c)

Figure 7.SEM micrographs of a) n-GaN, b) p-GaN, and c) $Al_{0.23}GaN$ etched under the following ICP conditions: 32 sccm Cl_2, 8 sccm BCl_3, 5 sccm Ar, 500 W ICP power, -150 V dc-bias and 2 mTorr pressure.

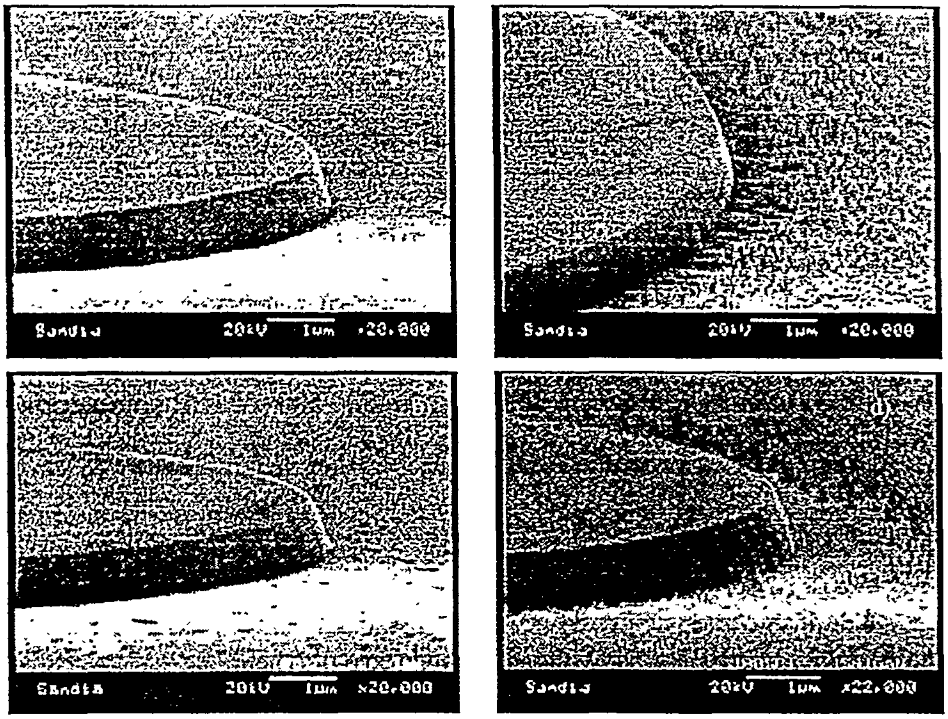
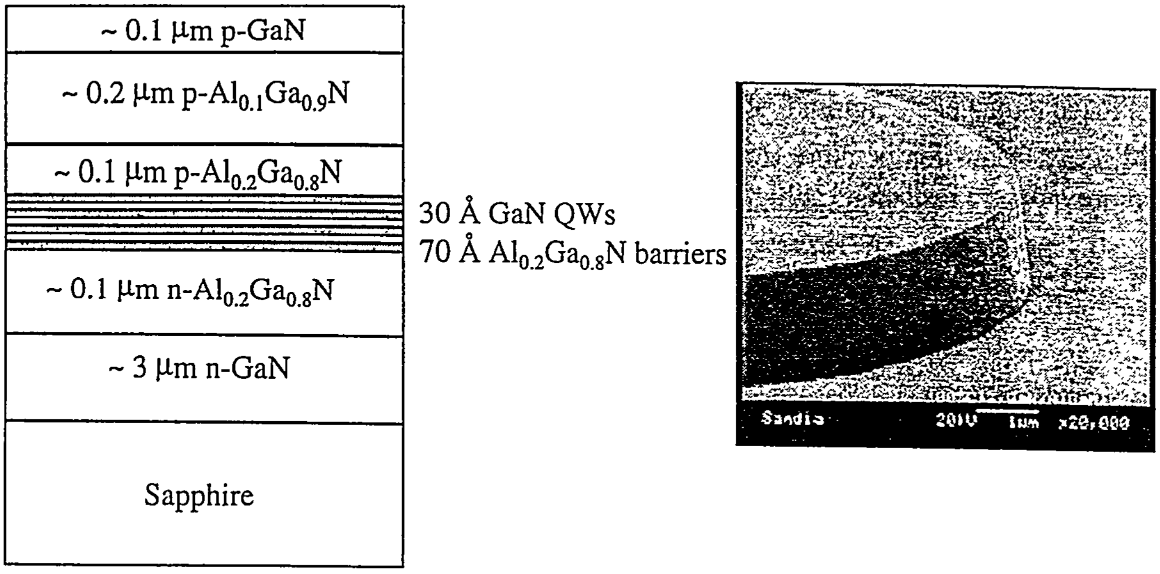


Figure 8.SEM micrographs of a) n-GaN, b) p-GaN, c) $Al_{0.17}Ga_{0.83}N$ and d) $Al_{0.23}Ga_{0.83}N$ etched under the following ICP conditions: 40 sccm Cl_2, 5 sccm Ar, 500 W ICP power, -150 V dc-bias and 2 mTorr pressure.

Surface roughness can also be used to evaluate the utility of an etch process. The surface roughness is often quantified using atomic force microscopy (AFM) and reported as root-mean-square (rms) roughness. Rough etch morphology often indicates a non-stoichiometric surface due to preferential removal of either the group-III or group-V species. For example, the rms roughness for GaN, InN, and AlN is plotted in Figure 9 as a function of $\%Cl_2$ in a Cl_2/BCl_3 plasma. The rms roughness for the as-grown samples were 1.00 nm for GaN, 5.98 nm for AlN, and 239.97 nm for InN. For GaN, the surface morphology remained smooth, (< 4 nm) as a function of $\%Cl_2$. The InN rms was normalized to the as-grown rms and scanned over a 40 x 40 μm area (as compared to 10 x 10 μm for GaN and AlN) due to the as-grown sample's rough surfaces. The InN surface



(a)

(b)

Figure 10: a) Schematic of the GaN/AlGaN LED structures. b) SEM micrograph of GaN/AlGaN quantum well structure etched in the ICP under the conditions: 8 sccm BCl_3, 32 sccm Cl_2, 2 mTorr pressure, 500 W ICP power, and 125 W cathode rf-power with a corresponding dc-bias of –200 V

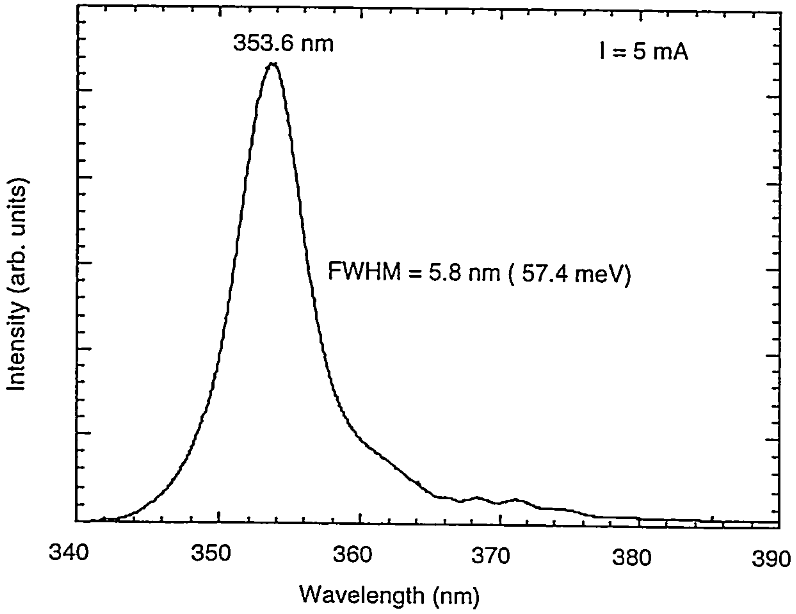


Figure 11: Room temperature electroluminescence of a 120 µm diameter GaN/AlGaN LED at I = 5 mA.

Electronic Devices

GaN/AlGaN heterojunction bipolar transistors (HBTs) have recently been reported in the literature.(28-30) Ren and co-workers have fabricated HBTs using a Cl_2/Ar ICP plasma to form the emitter and base contacts. The HBT structure is shown schematically in Figure 12a. The GaN etch rate was ~1100 Å/min under the following transconductance of 48 mS/mm was obtained with a maximum I_{DS} of 270 mA/mm. The JFET showed good pinch-off and breakdown voltage characteristics. In addition, the microwave measurement yielded an f_t of 6 GHz and an f_{max} of 12 GHz.

CONCLUSIONS

In summary, the BCl_3/Cl_2 plasma chemistry in combination with the ICP etch platform provides a very versatile etch process for the group-III nitrides. Etch rates ranging from 100 to 8000 Å/min with highly anisotropic profiles and smooth etch morphologies have been obtained. Etch processes have been optimized and applied to several photonic and electronic device applications with encouraging results. Understanding and minimizing plasma-induced damage mechanisms will become more important as device structures become more complicated and design rules shrink.

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