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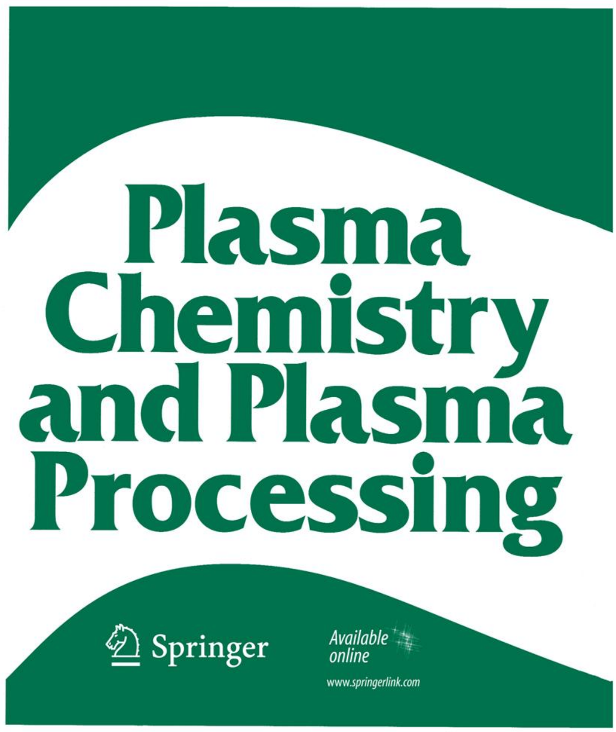

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ORIGINAL PAPER

Highly Selective and Low Damage Etching of GaAs/AlGaAs Heterostructure using Cl_2/O_2 Neutral Beam

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Abstract Highly selective and low damage etching of the GaAs cap layer on AlGaAs is essential in fabricating GaAs/AlGaAs high electron mobility transistors. The GaAs on AlGaAs was etched using a low energy Cl_2/O_2 neutral beam and the Schottky device characteristics fabricated on the exposed AlGaAs were compared with those fabricated after the etching using wet etching and a Cl_2/O_2 ion beam. Using a low energy Cl_2/O_2 ion beam or a Cl_2/O_2 neutral beam, highly selective etching of the GaAs cap layer to AlGaAs similar to wet etching could be achieved through the formation of Al_2O_3 on the exposed AlGaAs during the etching. When the electrical characteristics of the Schottky devices were compared, the devices fabricated after the etching using the neutral beam showed the best electrical characteristics such as electrical stability, low leakage current, higher barrier height, etc. by showing low damage to the exposed AlGaAs surface.

Keywords Neutral beam · Etch selectivity · GaAs · AlGaAs · HEMT

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Introduction

GaAs/AlGaAs heterojunctions are used extensively for various applications such as heterojuction superlattices, field effect transistors, injection lasers, solar cells, etc. because of close lattice matching between GaAs and AlGaAs. Especially, GaAs-based high electron mobility transistors (HEMTs) are an essential part of many monolithic microwave integrated circuits used in wireless communications. The fabrication of GaAs/AlGaAs HEMTs requires a highly selective and low damage gate recess etching process which selectively removes the GaAs cap layer on top of the AlGaAs schottky barrier layer prior to the gate metallization. During the selective removal of the GaAs cap layer, high etch selectivity between AlGaAs and GaAs layer, surface smoothness, low damage to the surface need to be satisfied simultaneously [1–3].

For the selective removal of the GaAs cap layer, wet etching or reactive ion etching (RIE) has been applied so far. In the case of wet etching, it has several advantages such as simplicity of the process, no damage on the etched surface, etc. On the other hand, the change in wet etch rate due to the solution chemistry with time, isotropic etching characteristics, and undercut are summarized as the disadvantages of the wet processing [4]. Reactive ion etching shows the controllable etch rate and vertical etch profile, however, leads to the damaged surface such as structural disruption and intermixing and, may cause the degradation of the processed devices due to charge-related damage caused by the reactive ion bombardment [5–7].

Many studies have been conducted previously and are currently being conducted to generate parallel and low energy neutral beams and to etch materials vertically without having electrical charging and physical damage [8–12]. In this study, to etch the GaAs on AlGaAs selectively and vertically with low damage and with low contamination, a low energy Cl_2/O_2 neutral beam was introduced. And, the effects of the low energy Cl_2/O_2 neutral beam etching on the etch characteristics of GaAs on AlGaAs and the Schottky diode characteristics fabricated on the exposed AlGaAs after the etching of GaAs were investigated. In addition, the device characteristics were compared with those fabricated after the etching of GaAs by wet etching and by Cl_2/O_2 ion beam etching.

Experimental

The samples used in this experiment were bulk n^+ GaAs wafers and GaAs (300 Å) cap layer/$n^+Al_{0.22}Ga_{0.78}As$ (5000 Å) barrier layer on n^+ GaAs wafer for Schottky diode fabrication. After the etching of the GaAs cap layer on the AlGaAs, a series of contact metal composed of Ti/Pt/Au (20/30/250 nm) was evaporated to form the Schottky diodes. Schottky diode pattern was defined by photolithography and to remove native oxide on the exposed AlGaAs, a wet cleaning using HCl/DI (1/3) was performed prior to metallization. The Ohmic contact to the backside of the GaAs wafer was formed by the e-beam evaporation of Ni/Au/Ge/Ni/Au (20/100/50/30/300 nm), followed by a rapid thermal annealing at 400°C for 45 s in N_2 ambient before the front GaAs etching was performed.

The samples were etched by a Cl_2/O_2 neutral beam, a Cl_2/O_2 ion beam, and a wet etchant for comparison. The wet etching was conducted by a mixture of H_2O_2 and H_3PO_4. For the Cl_2/O_2 neutral beam etching, a neutral beam system composed of a three-grid inductively coupled plasma (ICP)-type ion gun and a reflector installed just in front of the ion gun was used. At first, a parallel positive ion beam was extracted from the ICP source (Cl_2 flow rate: 12 sccm, O_2 flow rate: 3 sccm, rf power to the ICP source: 13.56 MHz, 300

Watts) using the three-grid system. Positive voltages in the range from +20 to +50 V were applied to the first gird of the ion gun for the control of the beam energy while −700 V was applied to the second grid for the control of the beam flux and while the third gird was grounded. The extracted positive ions were reflected on the parallel reflector having less than five degree sloped to the ion beam direction for neutralization. By using this type of neutral beam etching system, a high degree of neutralization and near parallel neutral beam could be obtained. The estimated neutralization efficiency measured after the reflection on the reflector was approximately 99% under the experimental condition [12]. For the operation as the Cl_2/O_2 ion beam etching, the reflector installed in front of the ion gun was removed while keeping the same operation condition as the Cl_2/O_2 neutral beam etching.

The current–voltage characteristics of the Schottky diodes were measured using a semiconductor parameter analyzer (Agilent, 4155A) to extract ideality factor and barrier height. The etched depth was measured using a step profilometer (Tencor Instrument, Alpha Step 500). The etch profile was observed using a field emission scanning electron microscopy (FE-SEM, Hitach S-4700). The roughness and chemical binding states of the etched surfaces were investigated using atomic force microscopy (AFM, Park systems XE100) and X-ray photoelectron spectroscopy (XPS, Thermo VG, MultiLab 2000, Mg K_a source), respectively.

Results and Discussion

Using the Cl_2/O_2 neutral beam, GaAs (300 Å) on $Al_{0.22}Ga_{0.78}As$ was etched as a function of the beam energy by changing the first grid voltage from +20 to +50 V and the etch depth of GaAs on AlGaAs measured as a function of etch time is shown in Fig. 1a. The ICP source power was fixed at 300 W while flowing 12 sccm Cl_2 and 3 sccm O_2 to the source. As shown in Fig. 1a, when the first grid voltage (~neutral beam energy) was +50 V, the etch rate (slope) of AlGaAs was similar to that of GaAs, therefore, after the etch depth of 300 Å, the etch depth was continuously increased with the increase of etch time. However, when the first grid voltage was decreased to +30 V, the etch rate of AlGaAs was lower than that of GaAs by showing lower slope when AlGaAs was exposed. And, when the neutral beam energy was lower than +25 V, the etching was stopped at 300 Å by showing almost infinite etch selectivity of GaAs to AlGaAs. As a reference, when bulk GaAs was etched at the first grid voltage of +25 V, the etch depth was increased almost linearly without stopping at 300 Å indicating the etch stop at the interface of AlGaAs.

Also, as shown in Fig. 1b, when the Cl_2/O_2 ion beam was used, for the etching of bulk GaAs, the etch depth was also increased linearly without stopping at the interface, however, when the GaAs (300 Å) on AlGaAs was etched, the etch stop at the interface similar to the case of the Cl_2/O_2 neutral beam could be observed even though the etch rate by the Cl_2/O_2 neutral beam etching is a little lower than that by the Cl_2/O_2 ion beam etching. The lower etch rate for the Cl_2/O_2 neutral beam etching at the same etch parameters is possibly related to the scattering of the ions during the reflection on the reflector. Therefore, by controlling Cl_2/O_2 neutral beam and ion beam energy, the infinite etch selectivity of GaAs to AlGaAs could be achieved.

The etch stop at the interface between GaAs and AlGaAs and an anisotropic etch profile could be observed by FESEM and the result is shown in Fig. 2 for the Cl_2/O_2 neutral beam etching with the first grid voltage of +25 V shown in Fig. 1. Similar results were also obtained for the ion beam etching condition with the first grid voltage of +25 V. In fact,

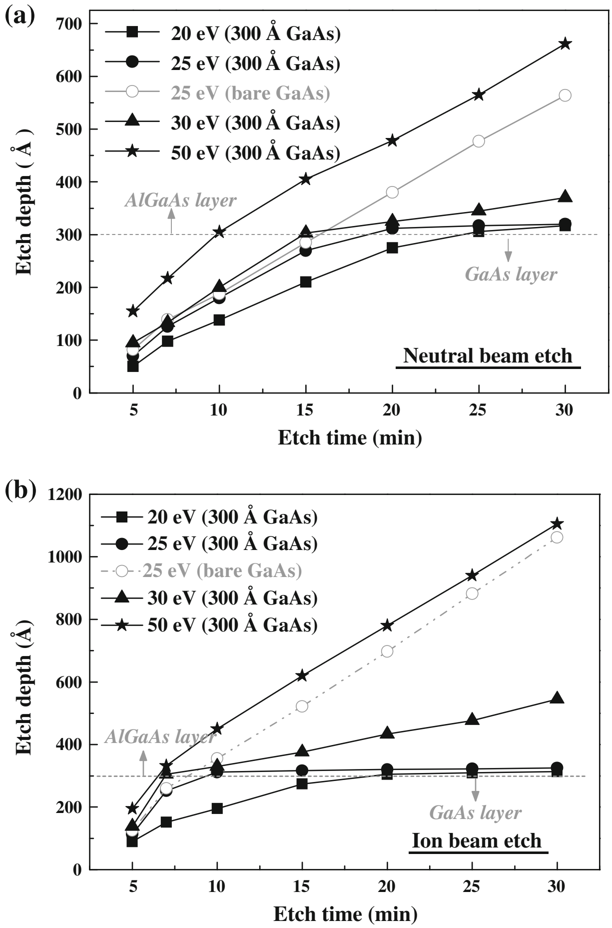


Fig. 1 Etch depth of bare GaAs and 300 Å GaAs on AlGaAs **a** by the Cl_2/O_2 neutral beam and **b** by the Cl_2/O_2 ion beam as a function of etch time

when the ion energy distribution was measured for the ion beam, two energy peaks composed of a low energy peak around 10 eV and a high energy peak which changes with the first grid voltage were observed.(not shown) The high energy peak energy was about 20 eV higher than the first grid voltage. The lower energy peak was not changed with the first grid voltage and appeared to be related to the energy of the ions diffused out from the ion gun while the high energy peak appeared to be related to the plasma potential + the first grid voltage. The etch selectivity and etch rate are believed to be related only to the high energy peak and intensity. In the case of the neutral beam formed after the reflection of the ion beam at the reflector, there is no reliable method in measuring the exact energy distribution of the neutral beam. But, when the energy differences between ion beam and the neutral beam was measured indirectly, about $\sim$ 12% loss of energy was estimated for the reflection at 5° angle [13]. Therefore, the infinite etch selectivity shown in Fig. 1 appears to be obtained at the actual beam energy of about 40 $\sim$ 45 eV.

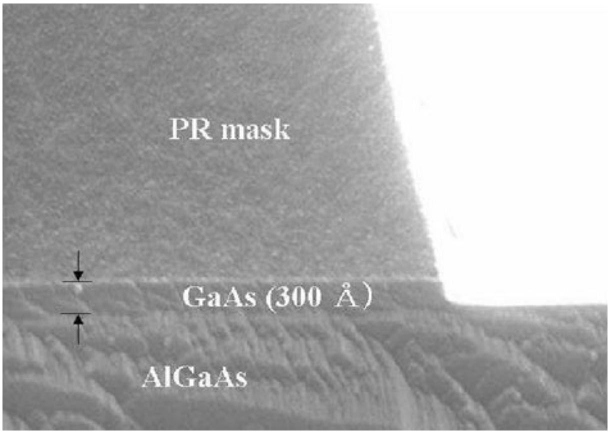


Fig. 2 SEM etch profile after the etching of 300 Å GaAs on AlGaAs using Cl_2/O_2 neutral beam with +25 V of the first grid voltage

The etch stop on the AlGaAs interface at the low Cl_2/O_2 bombardment energy obtained in our experiment is partially related to the lower vapor pressure of the $AlCl_3$ (B.P. 262°C) compared to the $GaCl_3$ (B.P. 201.3°C) formed on the etched surface as the etch product. However, it is believed to be more related to the formation of Al_2O_3 on the exposed AlGaAs after the removal of 300 Å GaAs during the etching by oxygen. Figure 3 shows the Al 2p XPS narrow scan data measured on the surface of the samples etched by the Cl_2/O_2 ion beam and the Cl_2/O_2 neutral beam for the first grid voltage of +25 V. As references, the Al 2p XPS data of the AlGaAs surface exposed by the wet etching of GaAs/AlGaAs and that of as-deposited AlGaAs surface were included. As shown in Fig. 3, the AlGaAs surfaces exposed after the etching by the Cl_2/O_2 ion beam and the Cl_2/O_2 neutral beam showed the Al 2p peak related to the formation of Al_2O_3 on the surface, while the AlGaAs surface exposed after the wet etching shows the Al 2p peak similar to that of as-deposited AlGaAs indicating no oxidation of AlGaAs. Due to the extremely low vapor pressure of Al_xO_y, the AlGaAs is not easily removed at +25 eV of neutral beam or ion beam and it can result in the etch stop at the interface.

In the etching of GaAs cap layer of GaAs HEMT device, the smooth surface is important for controlling the threshold voltage uniformity of the HEMT devices. The surface roughness after the etching of the GaAs on AlGaAs was investigated for the Cl_2/O_2 neutral beam etching and the Cl_2/O_2 ion beam etching for the first grid voltage of +25 V and the result is shown in Fig. 4. The surface roughness before the etching of GaAs on AlGaAs and that obtained after the wet etching by a mixture of H_2O_2 and H_3PO_4 are also included. As shown in Fig. 4, before the etching, the GaAs surface showed the rms surface roughness of about 2.4 Å. After the etching by the ion beam and the neutral beam, the roughness was slightly increased to 16.7 and 9.7 Å, respectively. However, after the wet etching, the surface roughness increased significantly to 48.7 Å possibly due to the severe micromasking effect by the residue remaining on the GaAs surface.

Using the AlGaAs exposed after the etching of the GaAs (300 Å) cap layer by the ion beam, the neutral beam, and the wet solution, Schottky diodes were fabricated by the evaporation of a series of contact metal composed of Ti/Pt/Au on the AlGaAs. The I–V characteristics of the Schottky diodes were measured and the results are shown in Fig. 5.

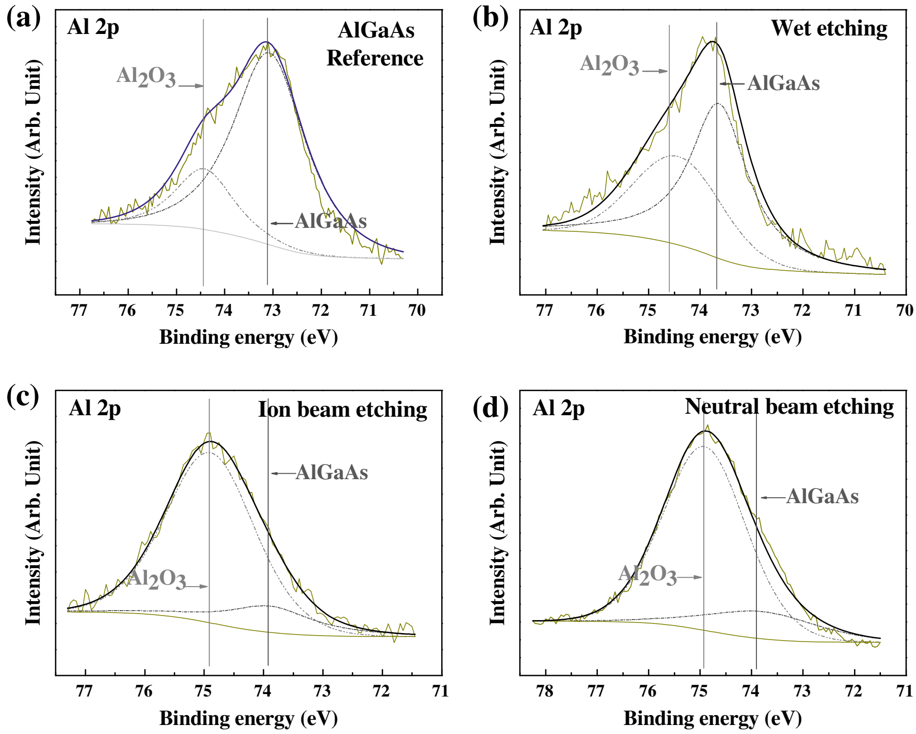
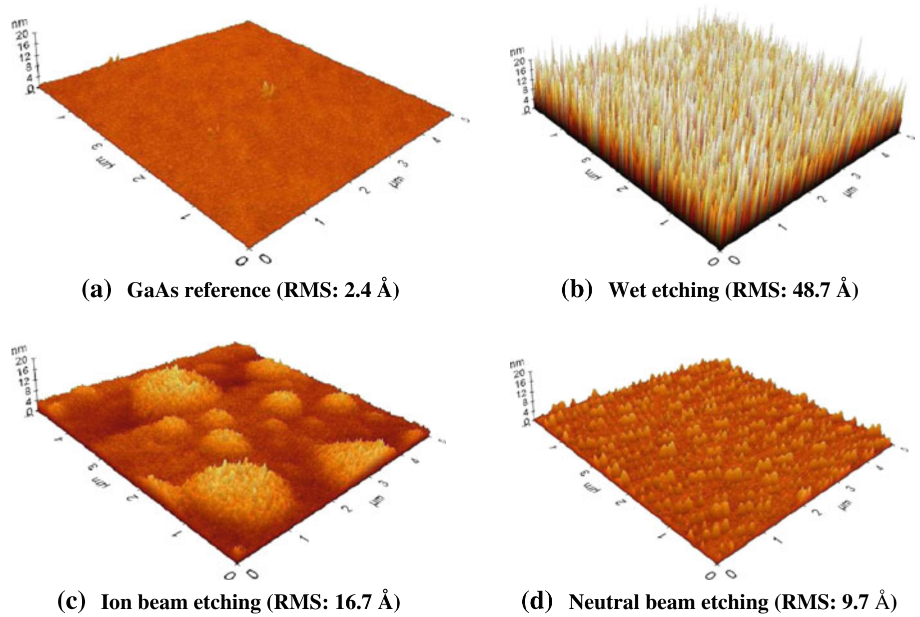


Fig. 3 The XPS narrow scan data related to Al atomic peak of AlGaAs surface before and after the etching of AlGaAs. **a** AlGaAs reference **b** Wet etching **c** Ion beam etching **d** Neutral beam etching

The ideality factor (η) and barrier height (Φ_B) of the Schottky diodes were extracted from the I–V curves using the following equations, $\eta = \frac{q}{kT}\frac{dV}{d(\ln J)}$ and $q\Phi_B = kT\ln(\frac{A^{**}T^2}{J_O})$,where, A^{**}(AlGaAs) = 97.2A/cm^2·K^2, $T = 300$ K, respectively, and the results are summarized in Table 1. The theoretical values of the ideality factor and the Schottky barrier height are known to be 1.0 and $\sim$0.87 eV, respectively [14]. As shown in Fig. 5 and Table 1, the Shottky diodes fabricated with the neutral beam etching exhibited better electrical characteristics than the diode fabricated after the ion beam etching and wet etching in terms of leakage current, Φ_B, and η even though the standard deviation is large (Due to the large standard deviation, the differences of the electrical characteristics between the ion beam etched devices and the neutral beam etched devices may be small, but, on the average, the neutral beam etched devices showed improved device characteristics.) In the case of wet etching, possibly due to the high surface roughness, the worst electrical properties were observed in addition to the problem related to reliability of the measured values. The lowest leakage current, the highest Φ_B and the lowest η (close to 1) of the Schottky diodes obtained by using the neutral beam are believed to be related to the smooth etched surface and no significant damage on the AlGaAs surface using a low energy beam. In addition, the use of Cl_2/O_2 neutral beam instead of the Cl_2/O_2 ion beam may have protected the surface from the plasma-induced damage related to charge of the ions even though more investigation is need to identify the exact reason for the improvement of the electrical properties.



(a) **GaAs reference (RMS: 2.4 Å)** **(b)** **Wet etching (RMS: 48.7 Å)**

(c) **Ion beam etching (RMS: 16.7 Å)** **(d)** **Neutral beam etching (RMS: 9.7 Å)**

Fig. 4 Surface roughness on AlGaAs surfaces evaluated by AFM after the removal of 300 Å GaAs on AlGaAs

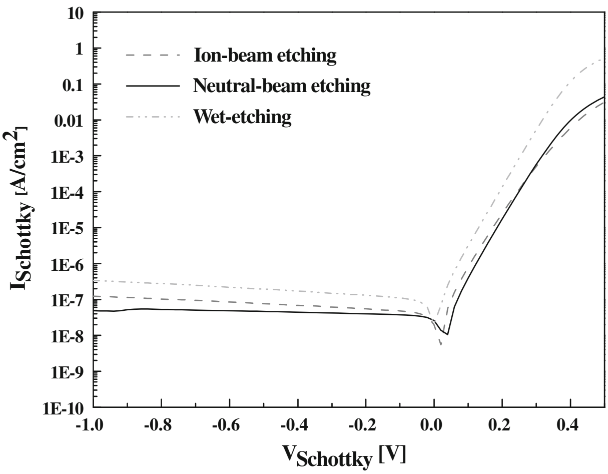


Fig. 5 I-V characteristics of the Schottky diode fabricated after the wet etching, ion beam etching and neutral beam etching

Table 1 Summary of the parameters of the Schottky diodes fabricated

	Wet etching	Ion beam etching	Neutral beam etching
η (Ideality factor)	1.02 ± 0.31	1.16 ± 0.18	1.05 ± 0.11
Φ B [eV] (Barrier height)	0.84 ± 0.07	0.86 ± 0.09	0.89 ± 0.07

Conclusions

In this study, the GaAs (300 Å) cap layer on AlGaAs was etched using the Cl_2/O_2 neutral beam at a low energy, and the etch characteristics and the Schottky diode characteristics fabricated after the etching by the neutral beam were investigated and compared with those etched by the Cl_2/O_2 ion beam and a wet solution. By using a beam energy lower than +25 V, GaAs could be etched highly selectively to AlGaAs by showing the etch stop on the AlGaAs interface for both the Cl_2/O_2 ion beam and the Cl_2/O_2 neutral beam due to the formation of Al_2O_3 on the exposed AlGaAs after the etching of GaAs during the etching by oxygen. When the electrical characteristics of the Schottky diodes fabricated on the exposed AlGaAs were measured, the device fabricated after the etching by the neutral beam showed, the lower leakage current, higher Schottky barrier height, and lower ideality factor compared to that fabricated after the etching by the ion beam possibly due to the lower charge related damage to the surface including the smoother surface. Therefore, it is believed that, using the low energy Cl_2/O_2 neutral beam, GaAs/AlGaAs HEMTs could be successfully fabricated by showing no charge related damage in addition to high GaAs cap layer etch selectivity over AlGaAs, highly anisotropic etch profile, etc.

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