Dynamic scaling of plasma etched InP surface

DYNAMIC SCALING OF PLASMA ETCHED InP SURFACE

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Abstract

Dynamical microroughening of the etch front of InP (100) due to Electron Cyclotron Resonance plasma etching was investigated. A quantitative study of the etch front morphology shows that the scaling law holds and the observed structure is self-affine. The low value of the growth exponent ($\beta = 0.37$) indicates that neither plasma reemission nor geometrical shadowing controls the Electron Cyclotron Resonance etching of InP.

I. Introduction

In modern microelectronic device fabrication dry etching technique is a major tool in thin film pattering. Decrease of the device sizes down to nano scale puts high demands on the quality of the processed surface. Extensive use of the InP based materials in electronic and photonic integrated circuits makes the investigation of InP surface modification during the dry etching an important issue. However, a few studies have been done on plasma etch front roughening despite the widespread use of this technique. Most of them were performed on Si [(1-3)]. InP surface morphology was studied in the case of ion sputtering with either O_2^+ [(4)] or Ar^+ [(5)] ion bombardment.

Electron Cyclotron Resonance (ECR) dry etching is the most commonly used technique to provide the low-damage smooth surface of InP. The chemistry of the ECR etching is well understood, but the surface morphology is not. Atomic Force Microscopy (AFM) measurements allow to investigate the development of the surface morphology with a high spatial resolution. AFM data can then be used to analyze the evaluation and dynamics of the surface morphology[(6)].

Recent experimental work on Si suggests the reemission and self-shadowing model[(3)]. According to this model, valleys on the surface will receive more redistributed etchant than peaks. Therefore, the valleys have a higher etching rate than the peaks, which causes instability in the morphology evolution. Our experiments show that this model does not apply to the ECR etching of InP. The dry etching of InP leads to the self-affine, not self-similar surface morphology as reported for the silicon surface.

II. Experimental

The dry etching of p-type (Zn, $2x10^{18}cm^{-3}$) (100) InP was performed in an ECR etch reactor.

The plasma etch reactor utilizes 2.45 GHz excitation source with a RF (13.56 MHz) biasing capability. The ECR etching process was optimized in terms of the etch rate and the smoothness evaluated by a surface profiler and a scanning electron microscopy, respectively. The etching process was performed using $CH_4/H_2/Ar$ (10:18:8 sccm) discharges at a pressure of 1 mTorr and a microwave power of 150 W. The DC_{bias} was kept at ~ -200 V. Under these conditions InP etching dominates over the polymer formation. The etch rate was

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18 ± 2 nm/min. The samples were etched over a period ranging from 1 to 60 min. An atomic force microscopy (AFM) image of 512x512 data points was obtained for different etch times both in tapping and contact modes. The scan size extended from 200x200 nm^2 to 10x10 μm^2.

In order to obtain reliable statistics, it is required that the scan size exceeds 10ξ, where ξ is the lateral correlation length [7], the typical distance over which the heights of the points on the surface are correlated. An estimate of the ξ value (~100nm) for the maximal etch time in our experiments (t=60min) proves that the scan range extension was sufficient.

To check for a possible dynamic scaling behavior of the etched InP surface, we have determined the values of the roughness exponent (α), the growth exponent (β) and the reciprocal dynamic exponent (z), which are dependent if the roughening process obeys the scaling law:

$$z=\alpha/\beta \qquad (2.1)$$

III. Results and Discussion

Fig. 1 shows the surface of InP for the different etch times. Already for the etching time of 1min, the surface morphology significantly differs from that for the reference surface. The surface morphology is relatively flat with holes and grains. As the etch time increases, holes and grains on the surface become bigger.

The method used for the determination of α and β for a particular interface depends on the information available. Obtaining these scaling exponents helps to identify the physical mechanism that governs the surface formation. Experiments may not be able to follow every detail of the temporal evolution of the roughening, and in the present study we analyze only the final interfaces.

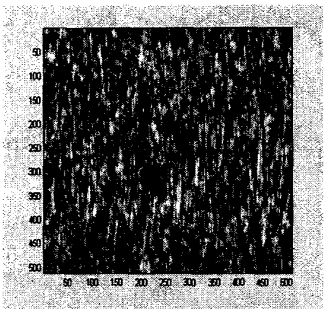
The local interface width w characterizes the roughness of the etch front. Another quantity that scales in the same way as the interface width is the height-height correlation function. To follow the surface roughening, we have analyzed the height-height correlation function:

$$H(r)= \langle [h(r) - h(0)]^2 \rangle \qquad (3.1)$$

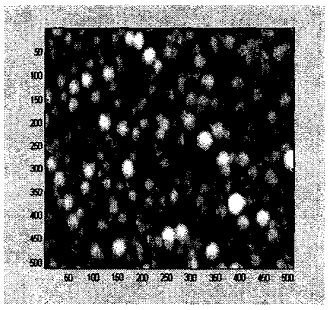
where $h(r)$ is the surface height at the position r (x,y), the brackets <...> stand for spatial and ensemble averages.

Fig. 2 shows the correlation function as calculated for different etch times. $H(r)$ is found to obey a simple scaling relation: for distances less than the lateral correlation length ξ it increases as a power of r, and for all etch times is described by a single value of the roughness exponent α:

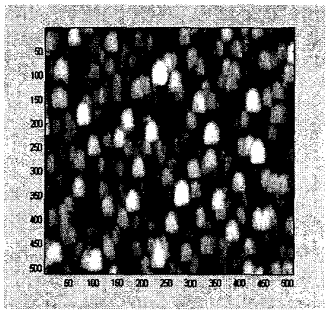
$$H(r) \sim r^{2\alpha} \qquad \text{for } r<<\xi \qquad (3.2)$$



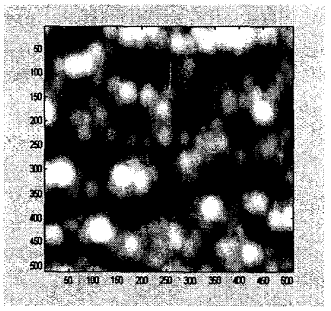
reference



t=1min



t=10min



t=60min

Fig.1 AFM images of plasma etched InP for t=1,10,60 min and the reference surface. The scan sizes are 500x500 nm^2. The data scale for the reference –2.9nm, for 1min etch – 4.9nm, for 10min etch – 7.1nm, for 60min etch – 24nm

The same roughness exponent describes scaling of the interface width. We found α=0.73±0.04.

While measurements of the roughness exponent gives a first indication of the kinetic roughening, to establish the dynamic scaling one has also to analyze the growth exponent. β characterizes the time-dependent dynamics of the roughening process:

$$w(t) \sim t^{\beta} \qquad (3.3)$$

The interface width can be obtained from the relation

$$H(r) \sim 2w^2 \qquad \text{for } r>>\xi \qquad (3.4)$$

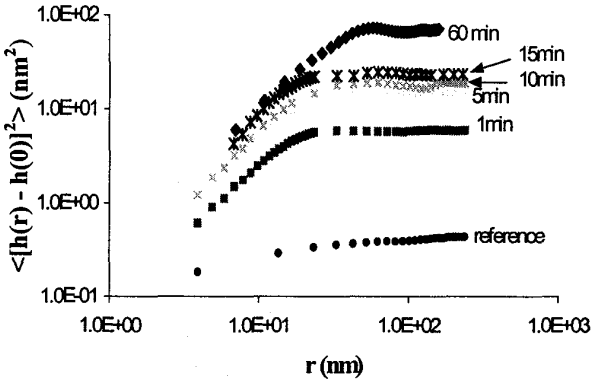


Fig.2 The height-height correlation function H(r, t) as a function of the distance for different etch times.

We found that the interface width evolves with the growth exponent β=0.37±0.02 (see Fig.3 where we plotted the interface width and the lateral correlation length versus etch time).

The lateral correlation lengths were determined independently via power density analysis. Fig.4 gives an example of the power spectrum for 15min etched surface. The lateral correlation length as a function of etching time gives the reciprocal dynamic exponent z^{-1}=0.48±0.03. The power density analysis clearly shows that the scaling law $z=\alpha/\beta$ holds.

These results are very different from the results reported for the dry etching of Si [3]. In (3) it was found that the plasma reemission plays an important role in the etching of Si with CF_4 and O_2 gas mixture. Calculated values of the scaling exponents (α=0.96, β=0.91, z=1.05) significantly differ from our results. The experiments on ion bombardment also show a high value of the growth exponent (β=1) that indicates an existence of the surface instability. The source of the instability is the negative surface tension. It is balanced by the surface diffusion and

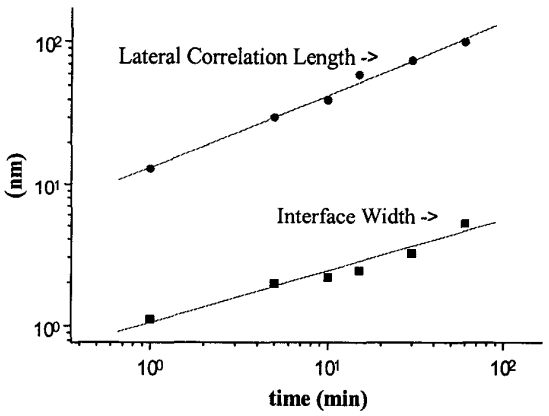


Fig.3 the interface width w and the lateral correlation length ξ versus time.

can lead to the appearance of the ripple structure.

Root-mean-square (RMS) roughness measurements of the O_2^+ and Ar^+-induced morphology of InP surface showed cone formation[4]. The cone size depends on the ion energy. A model for cone formation under Ar^+ ion bombardment has been based on the idea of the In-enriched surface due to the preferential sputtering of phosphorous. The radiation-enhanced surface diffusion probably results in the agglomeration of indium atoms into indium clusters. These clusters seed the development of the cones because of the higher sputter rate of InP compared to that of In.

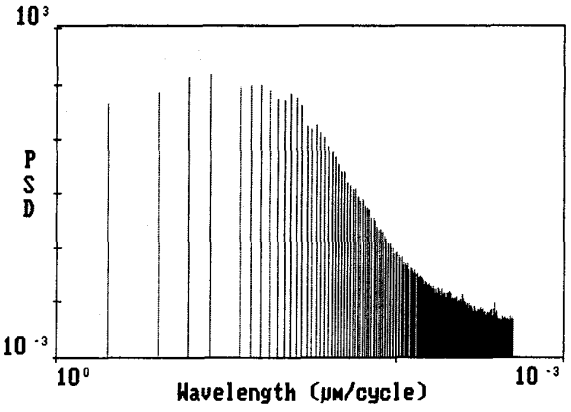


Fig.4 Power spectral density spectrum (PSD) from the AFM image of the InP surface etched for t=15min The PSD is averaged over all directions.

In the case of ECR dry etching the main etching mechanism is a chemical reaction that creates volatile products but not physical sputtering of the material. Also

the ion energies at the wafer are much lower. However, the InP surface is still depleted of P [8]. Our investigation of the p-type InP surface damages shows an increase in the Schottky barrier height after the ECR dry etching[9]. Ref.10 explains such behavior by the creation of indium-rich defects such as indium interstitials or phosphorous vacancies.

Values of the scaling exponents obtained in our measurements show that the evolving of the roughness along the surface is faster than in perpendicular direction. In (11) authors considered the four possible smoothing mechanisms: surface diffusion, volume diffusion, sputter redeposition and sputter removal. The exact values of the reciprocal dynamic exponent and the roughness exponent at this work are very different from our results. The surface and volume diffusions are evidently not the physical mechanism that plays a role in the roughening process of the InP surface because of the low ion energies. However, when the InP surface is indium enriched, the tops of the grains are mostly phosphorous depleted. In this case the Ar component of the gas mixture still plays the physical sputtering role and could initiate In sputtering from the top of the grain and its redeposition into the hole. Indeed, it was recently observed that adding Ar into ECR CH_4:H_2 plasma results in smoothening of the InP surface[12].

IV. Conclusions

We have investigated the evolution of the etch front of InP during ECR dry etching in $CH_4/H_2/Ar$ plasma. All three scaling exponents (α =0.73±0.04, β =0.37±0.02, z^{-1} =0.48±0.03) were determined by analyzing the AFM data. We observed clear scaling behavior of the surface roughening for etch times ranging from 1minute to 1 hour. The observed morphology is self-affine and not self-similar as reported for the Si surface. The low value of the growth exponent shows that neither plasma reemission nor geometrical shadowing controls ECR etching of InP. We suggest that the low values of the scaling exponents are provided by the In redeposition on the P-depleted surface.

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