Sub half micron structures with profile control on compound semiconductor substrates based on conventional i-line lithography

Dominik Schrade-Köhn[1,3], Philipp Leber[1], Reza Behtash[2], Hervé Blanck[2], Hermann Schumacher[1]

[1]University of Ulm, Institute of Electron Devices and Circuits, 89081 Ulm, Germany
[2]UMS GmbH, 89081 Ulm, Germany
[3]E-mail: dominik.koehn@uni-ulm.de; Phone +49 731 50 31590

Keywords: lithography, resolution enhancement, i-line, slant gate, resist profile, compound semiconductor

Abstract

Conventional i-line lithography was used as a basis for resist profile modification. The aim was the creation of slanted passivation openings for gate contacts with gate lengths between 0.1 and 0.5 µm.
It was shown that slanted profiles are possible by applying a post development bake to the Novolac photoresist. Dimension reduction was achieved by modifying the Novolac/bottom-anti-reflection-coating interface.
A modified approach combining plasma treatment of the photoresist lines with a bake sequence was used to create slanted features below 0.1 µm in the passivation layer.

INTRODUCTION

The driving force for smaller gate lengths in the Si-technologies for DRAM and microprocessor applications is not only speed issues but also integrating more transistors per chip and improving wafer area usage.
In FETs for high power applications wafer area usage is also an issue, but has no significant connection with the gate length since packing transistor cells too densely would commonly result in thermal problems.
In this case the driving force for smaller gate length is the strive for good performance in high frequency applications. Smaller gate lengths reduce the transit time under the gate and thereby increases the transit frequency f_t. For these structures small isolated features are needed whereas small pitch sizes between several structures are not required. Additionally the target gate lengths are between 0.1 and 0.5 µm for many of these processes. From an economic point of view optical lithography is superior to state of the art electron beam lithography processes provided that it is possible to apply low cost i-line processes in this dimension range.
Due to the high electrical fields present in such devices a slanted profile in the gate dielectric is beneficial for increasing device reliability. A smooth transition from substrate level to nominal dielectric thickness avoids the abrupt change of the electrical potential and therefore reduces the electrical field at the point where gate metal, passivation and semiconductor come into contact [1]. Additionally, positive impact on dispersion and breakdown voltage of such profiles has been reported [2].

EXPERIMENTAL

For the experimental part an i-line stepper with a fixed numeric aperture (NA) of 0.48 was used. All experiments were carried out using a state of the art Novolac-based i-line photoresist capable of 0.3 µm resolution. The photoresist was used on top of an organic bottom anti-reflection coating (BARC).
To provide complete coverage of the nonplanar surface from previous processings and to planarize the resist surface a relatively thick photoresist layer of 830 nm was used. The resist thickness value was chosen to act as a $\lambda/4$ refractive index match, reducing back reflection to the lens. An additional anti-reflective top layer onto the Novolac resin was not applied.
Two different industrially available BARC concepts were used in the experiments: a solvent-stable BARC requiring plasma etching and removal of the layer and a BARC suitable for wet development offering the opportunity of creating lift-off profiles and circumventing the potential risk of plasma damage to the substrate. Optically both resists presented very similar behavior during exposure.
The resulting resist profiles were determined on Au sputtered cross-sections of 0.5 µm lines (nominal dimension: reticle line x demagnification) using scanning electron micsroscopy (SEM).

RESULTS AND DISCUSSION

The usage of a relatively thick photoresist in combination with wafer topography led to some fluctuations in gate length due to the limited depth of focus (DOF). This was compensated for using an exposure dose slightly above the dose of clearance resulting in isolated features with repeatable shape and size between 350 and 380 nm.
Figure 1 shows the resulting profile which was used as starting point for profile and dimension modifications for the following three approaches:

I) Profile definition using a post exposure bake
II) Dimension reduction by modifying Novolak/BARC interface
III) Profile definition using a combination of plasma treatment and post development bake

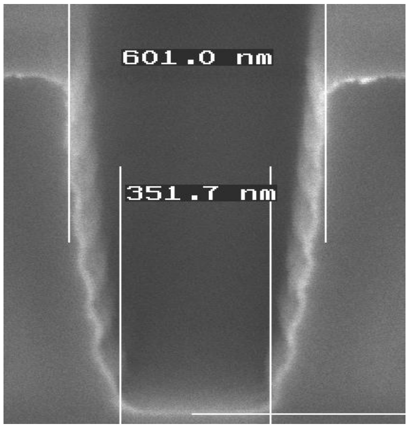

Figure 1 - Cross-section: resist profile of Novolac based photoresist on non-developable BARC after exposure and development

I) PROFILE DEFINITION USING A POST EXPOSURE BAKE

During a post development bake viscosity was decreased leading to shrinkage of the resist surface as shown in Figure 2.

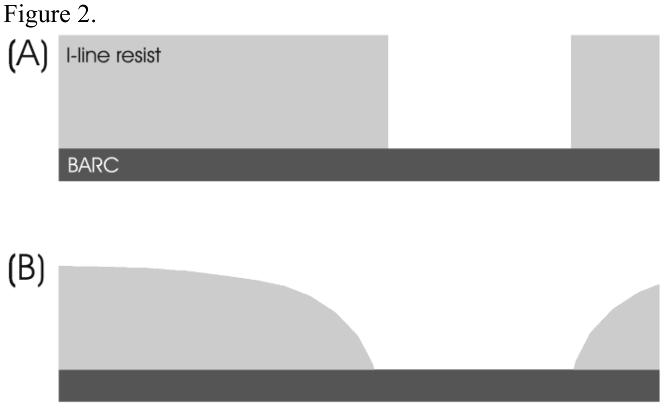

Figure 2 - Principle: Reduced viscosity during bake and surface tension of the Novolac layer lead to profile change from initial profile (A) to slanted profile (B).

This effect can be controlled by temperature, distance between the features, bake time and surface properties of the sub-layer. Bake time and distance between the features affect the resulting angle in the profile. The effect of feature distance on the resist profile is shown in Figure 3. With distances greater than 5 µm an influence on the profile was no longer observed.

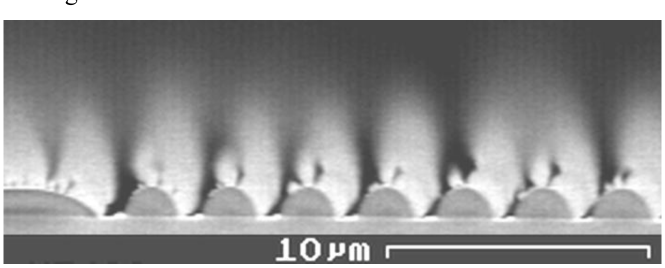

Figure 3 - Cross-section: Test structure with 2 µm bars in the center and > 5 µm at the edges; dependence of profile on distance between two single features is clearly visible

As suggested by the assumed mechanics behind the sidewall slanting the length of the resist opening was shown to be independent of the obtained angle in the Novolac resin.

The effect was examined by varying bake time and temperature starting from a reference temperature a.

With increasing bake time the spread in the resulting angle decreased significantly resulting in a very repeatable gate profile definition.

The duration of the post development bake showed no influence on the resulting profile on average or on the dimension of the resist opening when staying at or below a+30 K.

The influence of bake temperature on the angle is shown in Figure 4 for the optimum bake duration. An example for the resist profile (a+20 K post development bake) is shown in the upper left picture of Figure 6.

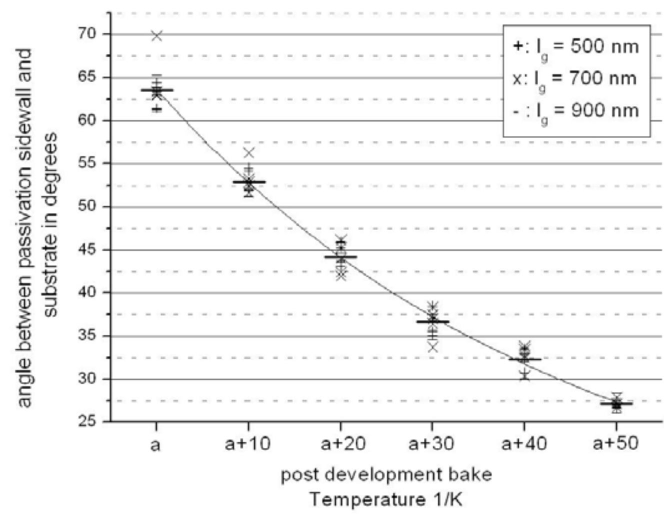

Figure 4 - Effect of post development bake of the resist on slanted gate angle in the passivation; showing independency of the angle from the gate length. l_g is the reticle opening*demagnification factor of the stepper optics

Nevertheless when transferring the profile into the passivation layer using some over etch time for process stability the dimension increases with increasing slant of the profile. This increase can be approximated using a simple geometric relation when knowing the etch rate and the over etch. This relation is given in Formula 1 for the simplification of totally anisotropic etching.

$$\Delta l_g = OE * \frac{1}{\tan\alpha} * \frac{ER_{nov}}{ER_{pass}} \qquad (1)$$

Resulting nitride profiles after anisotropic reactive ion etching and resist strip are shown in Figure 5. Here the onset of resist flow for T > a+30 K is visible in the corresponding passivation profiles.

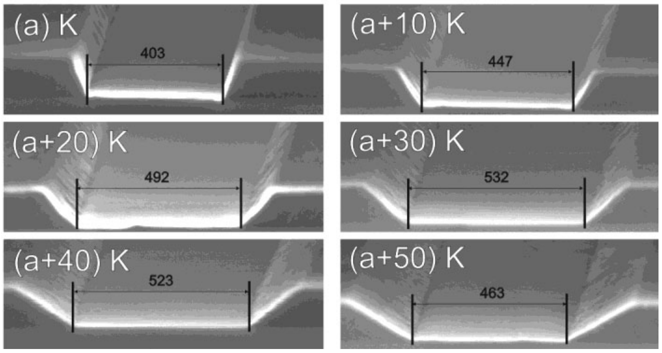

Figure 5 - Cross-section: Transferred structures with 50 % over etch (nominal value calculated from passivation etch rate and etch time) in the passivation layer after resist strip. Pictures correspond to the measured angles shown in Figure 4. Feature size is given in nm.

II) Dimension reduction by modifying Novolak/BARC interface

By treating the BARC with solvents, temperature activation, rinsing with de-ionized water and spin drying the layer was permanently modified. Changes in the bond structure of the BARC were proven by IR-spectrometry. Since the changes were only present in the fingerprint area[1] of the spectra it was not possible to determine the nature of the modification with this method. After application of the photoresist, lithography and development, the BARC modification repeatedly led to smaller feature sizes after the post exposure bake at a+20 K.

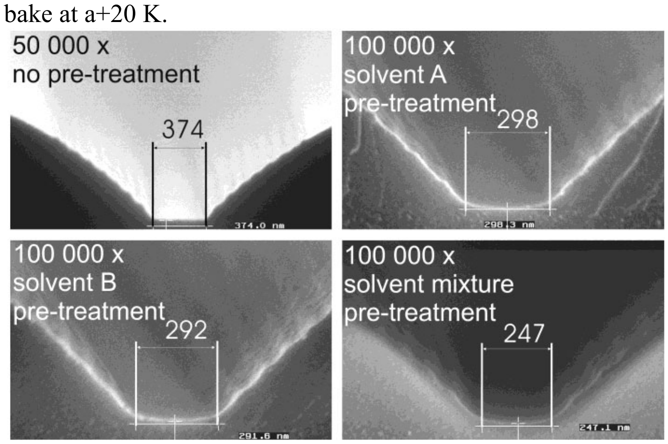

Figure 6 –Cross-sections: Profile in the Novolac resin on BARC after post development bake. BARC pre-treatments as given in the pictures

This is very likely due to a modified Novolac-BARC interface which reduces the interface friction.

As shown in Figure 6, without additional treatment of the BARC layer the dimension at the bottom of the opening slightly increases to ~375 nm. Using solvent A or solvent B modification this dimensions decreases to ~300 nm. The strongest effect was observed with a solvent mixture yielding ~250 nm bottom feature size.

III) Profile definition using a combination of plasma treatment and post development bake

In the next step a modification of the upper surface by a plasma treatment was examined. The aim was to harden the surface of the resist in order to avoid surface minimization during the post exposure bake. The interface to the BARC was assumed to be stable during the bake whereas viscosity of the I-line resist reduces. During the bake gravity forces will induce a change in resist thickness while resist volume is kept constant. These geometrical constraints only allow the upper resist edges to move into the openings until euquilibrium of forces is reached. This results in an inverse slanted profile as shown in Figure 7.

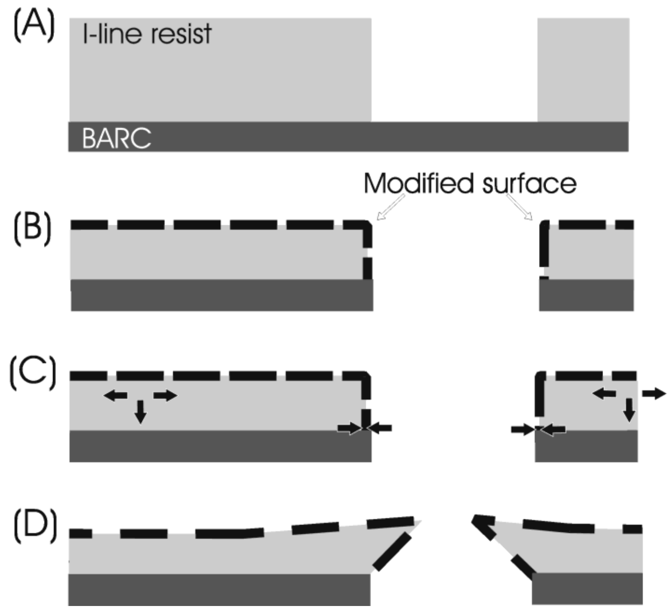

Figure 7 – Principle: Proposed mechanism for inverse slanted resist profile formation. (A) Lithographic line structure; (B) thickness reduction of Novolac, BARC opening and surface hardening during first anisotropic plasma etch; (C) principal model of intrinsic forces after the plasma etch; (D) during bake sequence the decreased viscosity allows for stress relaxation by deformation of the resist layer

This profile shape was confirmed in the experiment. In Figure 8 SEM cross-sections corresponding to the process steps described in Figure 7 are shown. Repeatability studies for this inverse profile are underway.

Regarding the resulting dimensions feature sizes below 100 nm were shown to be possible as shown in Figure 9.

Conclusions

It was shown that using an optimized i-line process with state of the art BARC technology it is possible to create slanted resist and passivation structures. While the initial process was still limited to approximately 375 nm resist openings, solvent treated BARC layers allowed to decrease feature sizes down to approximately 250 nm in the resist.

[1] Explanations of this expression as well as the following acronyms are given at the end of this manuscript.

Using a different approach with plasma modified Novolac resin surfaces the direction of photoresist slanting was reversed. Even though feature size increases during the opening of the passivation layer due to the slanting (over etch and non-isotropic behavior of the plasma) dimensions were reduced below 100 nm.

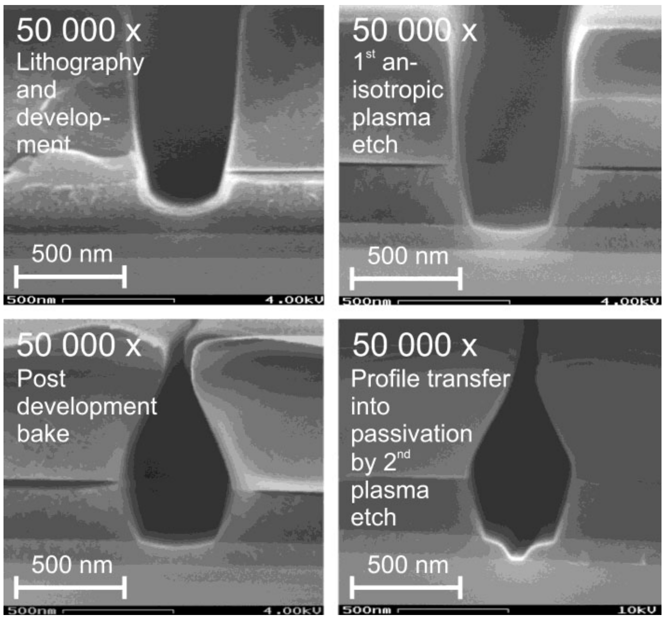

Figure 8 – Cross-sections. upper left: lithography and development; upper right: first plasma etch through the BARC layer; lower left: bake; lower right: profile in the passivation after the second plasma etch.

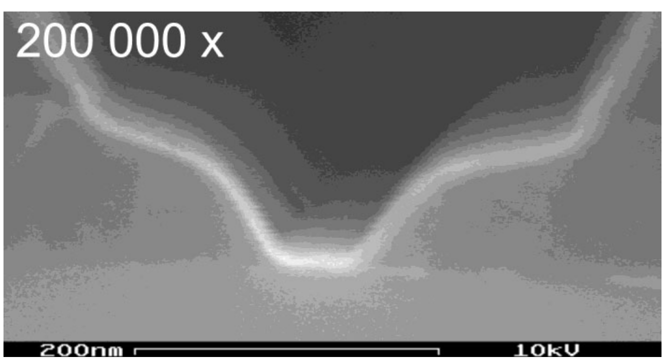

Figure 9 – Cross-section. Close-up of passivation profile from lower right picture of Figure 8.

ACKNOWLEDGEMENTS

This work was possible with the support of United Monolithic Semiconductors Ulm, GmbH (UMS) consisting in the usage of their equipment and complete financial coverage.

The authors would like to thank their colleagues at UMS. Especially Thomas Wiedenmann for good practical advice from production experience, Hüseyin Sahin for adaption and transfer of the coating processes onto production equipment, Hans-Peter Maucher for supplying appropriate dry etch processes and all people from the lithography shop for carrying out plenty of exposure variations with the i-line stepper.

REFERENCES

[1] M. Hosch, R. Behtash, J. R. Thorpe, S. Held, H. Blanck, K. Riepe, and H. Schumacher (2008). *The Impact of Layout and Technology on the DC and RF Performance of AlGaN/GaN HFETs* Proc. 20th Asia Pacific Microwave Conference, Hong Kong, P.R.China, December 16 - 19, 2008

[2] Y. Pei, R. Chu, N. A. Fichtenbaum, Z. Chen, D. Brown, L. Shen, S. Keller, S. P. DenBaars, U. K. Mishra (2007) *Recessed Slant Gate AlGaN/GaN High Electron Mobility Transistors with 20.9W/mm at 10GHz* Japanese Journal of Applied Physics, Vol. 46, No. 45

ACRONYMS

λ: wavelength

a: reference temperature for bake processes

BARC: Bottom Anti Reflection Coating

l_g: gate length (feature size)

f_t: transit frequency

OE: over etch in nm

ER_{nov}: etch rate of Novolac resin

ER_{pass}: etch rate of passivation

DOF: depth of focus

Fingerprint area: Transmittance pattern in the IR-spectra below 1500 cm^{-1} (λ higher than 6.7 µm)