REFERENCES

1. T. Watanabe *et al.* in "Proceedings of International Reliability in Physics Symposium," pp. 50-54 (1987).
2. K. V. Sichart, L. Do Thanh, Th. Kleinert, S. Röhl, and H. Reisinger, in "Reliability of Semiconductor Devices and Interconnection and Multilevel Metallization, Interconnection, and Contact Technologies," (PV 89-6) H. S. Rathore, G. C. Schwartz, and R. S. Susko, Editors, p. 227, The Electrochemical Society Softbound Proceedings Series, Pennington, NJ (1989).
3. A. Nishimura *et al.*, "Proceedings of International Reliability in Physics Symposium," pp. 158-162 (1989).
4. P. Hiergeist *et al., IEEE Trans. Electron Devices*, **ED-36,** 913 (1989).
5. K. H. Küsters *et al.*, in "ESSDERC 1989, 19th European Solid State Device Research Conference," Berlin, pp. 907-910, Springer Verlag, Berlin (1989).
6. M.-S. Liang, N. Radjy, W. Cox, and S. Cagnina, *This Journal*, **136,** 3786 (1989).
7. Y. Ohji *et al.*, in "Proceedings of International Reliability in Physics Symposium," pp. 55-59 (1987).
8. S. Mori *et al.*, in "Digest of Technical Papers, Symposium on VLSI Technology," p. 71 (1986).
9. J. Yugami *et al.*, pp. 173-176 of Extended Abstracts of 20th International Conference on Solid State Devices and Materials," pp. 173-176 (1988).
10. P. Suryanarayana *et al., J. Vac. Sci. Technol.*, **B7**(4), 599 (1989).
11. D. A. Buchanan *et al., Solid-State Electron.*, **30,** 1295 (1987).
12. S. K. Lee *et al., ibid.*, **31,** 1501 (1988).
13. R. Baunach *et al., Appl. Surf. Sci.*, **30,** 180 (1987).
14. R. Baunach *et al., J. Appl. Phys.*, **64,** 4567 (1988).
15. D. J. DiMaria *et al., Appl. Phys. Lett.*, **31,** 680 (1977).
16. D. J. DiMaria *et al., Appl. Phys.*, **51,** 4830 (1980).
17. I. C. Chen *et al., IEEE Electron Device Lett.*, **EDL-8,** 140 (1987).
18. J. Lee *et al.*, in "Proceedings of International Reliability in Physics Symposium," p. 131-138 (1988).

Fabrication of Non-Underetched Convex Corners in Anisotropic Etching of (100)-Silicon in Aqueous KOH with Respect to Novel Micromechanic Elements

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ABSTRACT

The planes occurring at convex corners during anisotropic etching of (100)-silicon in aqueous KOH were identified as {411}-planes, with the help of a specially developed measuring technique. The etching rate of these planes in relation to the rate of the {100}-planes declines with increasing potassium hydroxide concentration. In contrast, the temperature dependence of this etch rate ratio is negligible in the relevant range between 60°C and 100°C. Based on these results, special structures suited for the compensation of the undercutting in the case of very narrow contours were developed. With the help of these structures it is feasible to realize, for instance, bent V-grooves or structures with a very low ratio between lateral expansion and etching depth, *e.g.*, a discrete pyramid-trunk with minimum dimensions on the wafer surface. This offers access to completely new applications, among others spiral channels with double-sided anisotropic etching for micromechanical heat exchangers; corrugated diaphragms stiffened in two dimensions with low thermal resistance and arbitrary wall thickness; and bellow structures for decoupling mechanical stresses between micromechanical devices and their packaging. Furthermore, this technology paves the way for designing novel types of accelerometers and inclination sensors with external seismic mass.

Although micromechanics can take advantage of considerable progress in the field of etching technology, hitherto many structures could not be realized in aqueous KOH etching solution, which is easy to handle and to a large extent harmless (1, 2). For convex corners, which have to be protected from undercutting for most applications, rugged surfaces with badly defined etching rates have to be accepted with almost all known compensation structures (3). This impairs the reproducibility of the devices. On the other hand, certain structures, *e.g.* rectangular bent V-grooves or a four-sided regular pyramid-trunk (4) with an extremely small base, could not be realized with the compensation structures available up to now. The following presents the basic etching technology and the development of suitable compensation structures to avoid undercutting with respect to the fabrication of special micromechanical structures.

Experimental

The fabrication of the above-mentioned elements and the development of suited compensation structures requires detailed investigation of the undercutting occurring at convex corners during anisotropic etching of (100)-silicon in KOH solution. These essential experiments were carried out with the help of the following test structures. Simple squares, oriented along the <110>-direction or with error orientations up to a maximum of 5° in gradations of 1° on a test mask, were used primarily for the determination of the crystal planes generated and the parameters determining their etching rate. In addition, we integrated some squares with small <110>-oriented beams as they are used for the compensation of corners in (5); the beam width was varied between 20 μm and 80 μm. <100>-n-Si wafers passivated with 100-nm silicon oxide and 400-nm silicon nitride were used for the experiments. The etching depth varied up to a maximum of 300 μm. The etching tests were carried out in pure aqueous KOH solution with a KOH content of 15 to 50 weight percent (w/o) at temperatures of 60°C to 100°C. The KOH concentration was checked with areometers after each test run.

The crystal planes occurring in the case of undercutting were identified, first, by exact measurement of the under-

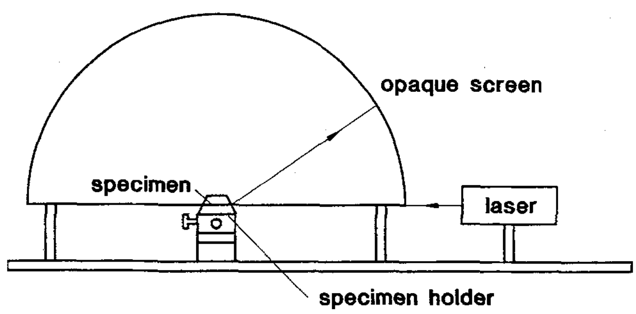

Fig. 1. Device for measuring crystal planes

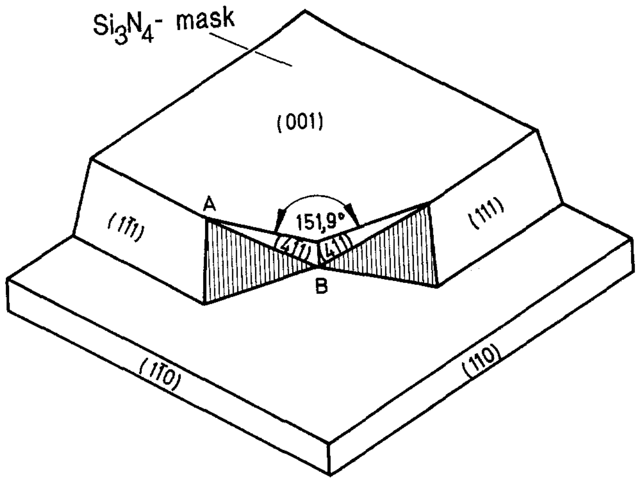

Fig. 2. Planes occurring at convex corners during KOH etching

etched mask sectors with an exact line-width measuring unit. Second, a measurement arrangement permitting the identification of each crystal plane laid free by laser reflection was developed. The concept of the arrangement is as follows (Fig. 1). An HeNe alignment laser points in the x-direction (according to the coordinate system of the silicon crystal) onto the underetched convex corner of the specimen. The arrangement is covered by a hemispherical opaque screen calibrated for all crystal planes of a cubic crystal up to Miller index 4, to the end that each crystal plane appearing at the crystal surface can be read off directly with the help of its laser reflection.

Results

The experiments showed that the undercutting of convex corners in pure KOH etch is determined exclusively by {411}-planes. Other planes could not be observed, either for error-oriented squares, or for different KOH concentrations. Figure 2 depicts a REM picture of the structure created. The {411}-planes are only laid entirely free above a diagonal line dividing the underetched sector from the frame up to the center (AB in Fig. 3). In the remaining sector they are overlapped by a rugged surface. Here only fractions of the main planes of the crystal can be detected.

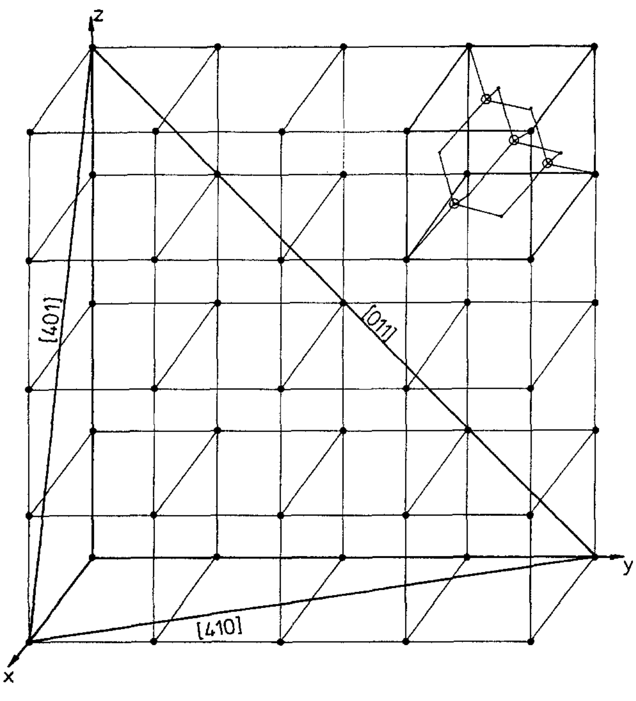

Fig. 3. Location of the {411}-planes in a silicon crystal

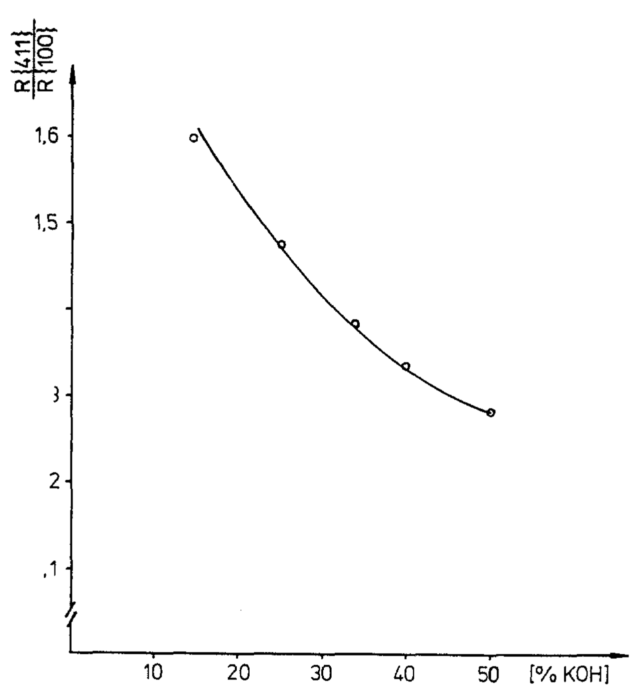

Fig. 4. Etching rate of the {411}-plane relative to the {100}-plane

At the water surface, the sectional line of a {411}- and a {111}-plane points in the <410>-direction, forming an angle of 30.96° with the <110>-direction. This is in accordance with Seidel (6), who found in this angle a minimum of activation energy, equaling a maximum of lateral undercutting without determining the crystal planes. However, the results of Bean (7) using KOH, propanol, and H_2O, and Puers and Sansen (8) determining the planes as (331), or planes oriented in the <130>-direction, were not confirmed.

In the temperature range between 60°C and 100°C, the etching rate of the {411}-planes relative to the etching rate of the {100}-planes does not depend on the temperature. Figure 4 depicts the dependence of this etch rate ratio on the KOH concentration. The value declines with increasing concentration. However, etching with a concentration of more than 40 w/o is not recommended, since the surface quality of the entire etching structure declines drastically. In the range from 0.01 Ω-cm up to 5 Ω-cm investigated, we

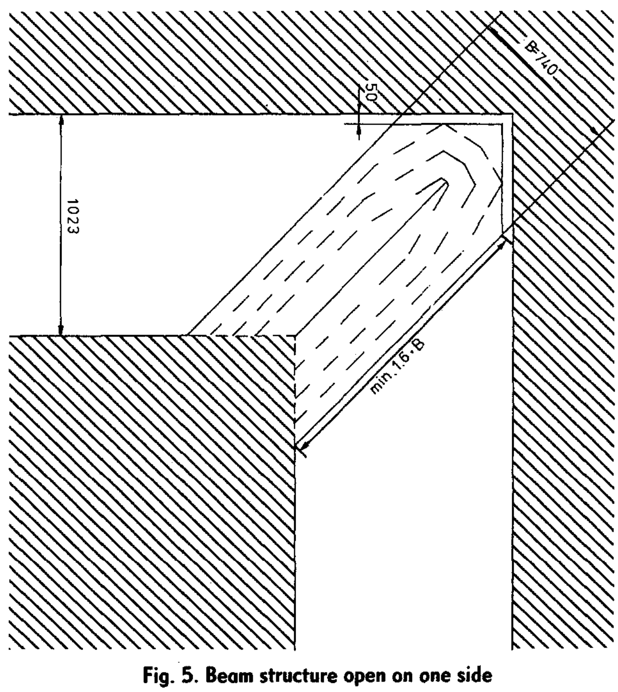

Fig. 5. Beam structure open on one side

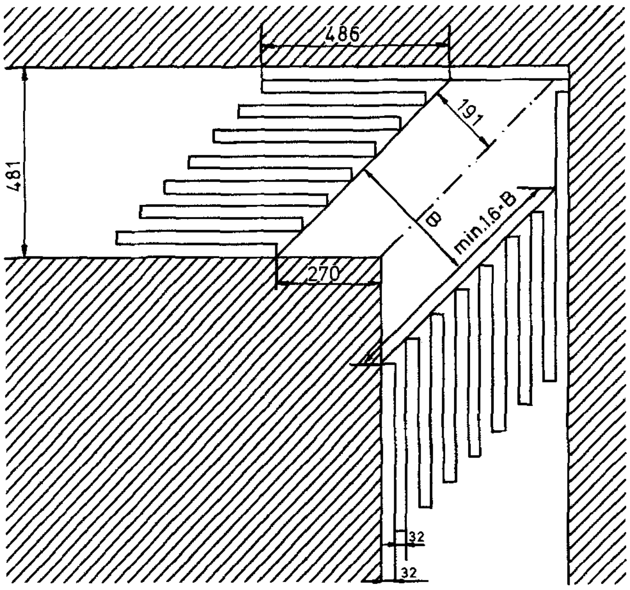

Fig. 6. Corner compensation structure for a rectangular bent V-groove.

could not determine a dependence of the etch rate ratio on the specific resistivity.

The undercutting of other structures with convex corners, too, is determined by {411}-planes. In the case of narrow beams, however, these planes only occur in a small area directly under the mask. Otherwise, they are overlapped by the rugged surfaces already mentioned. Therefore, they do not render optimal results for an application in corner compensation. Moreover, rugged surfaces are subject to high distortions with respect to the etching rate.

The test to compensate the undercutting by means of triangles, as suggested by Wu and Ko (9) for etching in other etching solutions (the triangles ought to contain the <410>-direction), too, led to rugged surfaces which always occur in connection with the {411}-planes. Although these triangular structures can be used to generate convex corners in the upper section of the etching groove, they laid entirely free to the etching bottom.

One way of creating convex corners formed by two {111}-planes and laid free to the bottom was presented by Buser and de Rooij (4). Beams oriented in the <010>-direction and added to a convex corner are subject to undercutting formed by vertical {100}-planes at both sides. In the case of suitable dimensioning, a vertical diaphragm giving the convex corner free from the wafer surface to the etching bottom, when the etching depth is reached, results shortly before the bottom is reached. The width of these beams, which in this compensation structure determine the minimum dimensions of the structures to etch, has to be twice the etching depth. These beams either can connect two opposite corners and simultaneously protect from undercutting, or can be added open to individual convex corners (Fig. 5). However, in this case they have to be long enough to avoid being completely underetched by {411}-planes, starting from the open and before the etching depth is reached. The length depends on the concentration of the etching solution used. For instance, a 33% KOH etchant requires a ratio between beam length and width of at least 1.6.

The compensation structures known hitherto generally are not, or are only to a limited extent, suited for the realization of complex and exactly defined structures, due to the rugged surfaces and the high spatial requirements. In particular, bent V-grooves cannot be realized because of the latter. Since the best results for the formation of convex corners with reproducible even surfaces can be obtained via the compensation structure with a <010>-oriented beam, a special structure was developed combining various compensation structures. The main element is a <010>-oriented beam. At the two long sides this band is fanned out into narrow beams. For the realization of a bent V-groove the <010>-oriented beams are fixed at one side of the outer edge of the groove (Fig. 6).

As described, the narrow beams are underetched by the rugged {411}-planes until reaching the <010>-oriented beam. Between the narrow beams there are only concave corners. At these points the {411}-planes are stopped by the vertical {100} planes with slower etching characteristics, and align with these planes in the course of the etching process. Based on Fig. 7, a formula for determination of the dimensions of the compensation structure can be given.

For the width B of the beam, the following condition is applicable: the beam has to be wide enough to avoid being completely underetched by {411} planes from the front side, before it is entirely underetched by {100}-planes. The length, L, of the beams can then be calculated with the equation

$$L = (H - B/2) \cdot V \cdot 1.03 \cdot 1.94$$

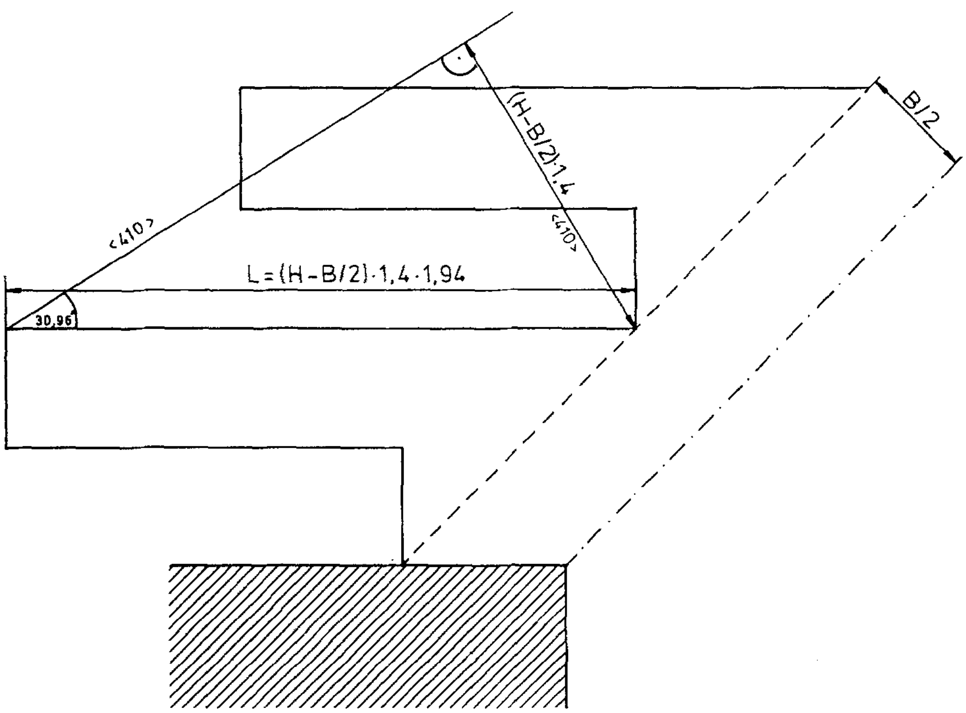

Fig. 7. Dimensioning of a compensation mask.

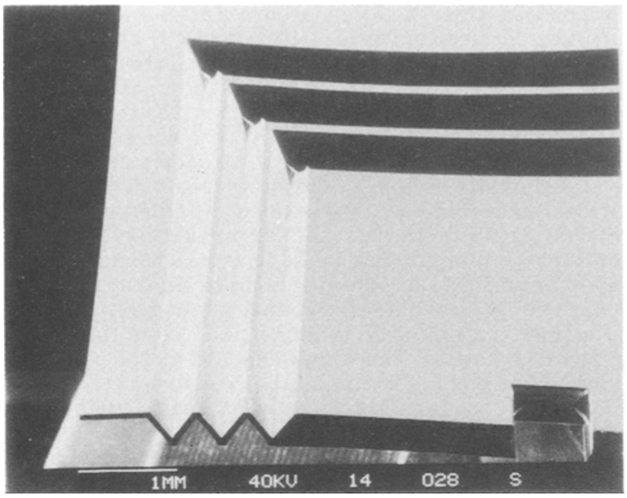

Fig. 8. Mechanical bellow-element for pressure sensors assembly (REM)

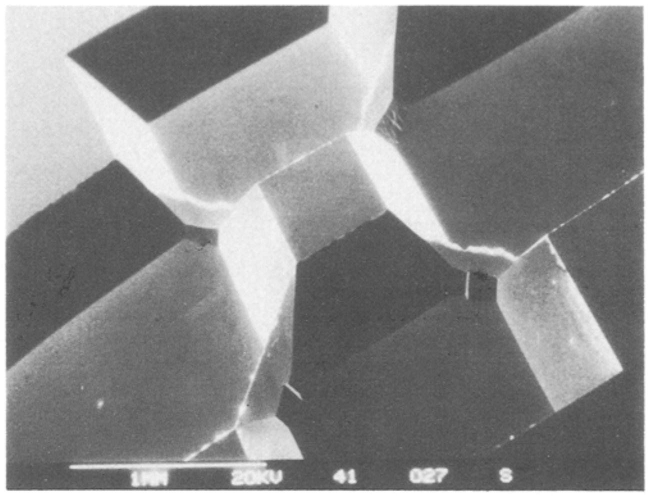

Fig. 10. Pyramid-trunk, etched in (100)-silicon (REM)

with H = etching depth at the deepest position of the device, and V = ratio of the etching rates between the {411}- and the {100}-planes. The factor 1.03 takes into consideration the inclination of the {411}-planes against the vertical line, and the factor 1.94 the angle formed between the <411>-direction and the <010>-direction. The width of the narrow beams does not influence the length required. It is best determined according to the optimal division of space available into beams and clearances of the same width. The beam width should vary between 15 μm and 30 μm, since this guarantees the alignment of the {411}-planes to the vertical {010}-planes. Simultaneously, the beams are wide enough to avoid premature undercutting by lateral effects.

Figure 8 depicts an example of several sequential V-grooves. Towards the bottom the grooves are not laid entirely free, since otherwise mechanical stress in these areas can cause a high notch effect, which may lead to a premature rupture of the device under the impact of additional forces. Defined setting of the size of these remnants is feasible via the beam width.

In the fabrication of a four-sided regular pyramid-trunk with minimum dimensions, the conventional edge compensation structures with <110>-oriented beams led to an entire distortion of the structure demanded, due to the rugged surfaces. With the application of the beams suggested by Buser and de Rooij, the side length on the mask is limited to the etching depth multiplied with a factor of $2\sqrt{2}$.

In Fig. 9 a suitable compensation structure for the realization of a pyramid-trunk with minimum dimensions is shown. When determining the beam dimensions, care has to be taken that the {411}-planes and the related rugged surfaces are aligned to the vertical <100>-wall to avoid its complete disintegration before they reach the bottom. Figure 10 depicts the vertical <100>-walls shortly before complete lateral underetching occurs. The still-visible remnant of the rugged surface will align to this wall before the etching process is terminated. The narrow beams can be dimensioned with the help of the above-mentioned rules and equations.

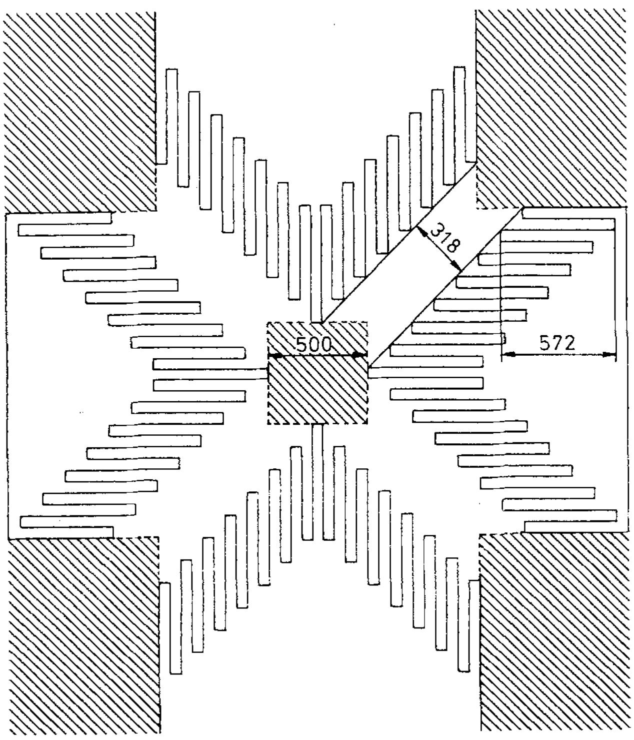

Fig. 9. Corner compensation mask for a pyramid-trunk

Conclusion

The corner compensations presented offer an entirely new way of fabricating micromechanical elements and devices with KOH etching technology. For instance, V-grooves with rectangular bends are needed for special applications. Simulations (10) proved that mechanical stresses on micromechanical sensors caused by the assembly have a negative effect on the long-term stability and the temperature dependence of the characteristics. This negative effect on the characteristics of a sensor can be avoided by using a bellow structure. By aligning a sequence of several bellow structures, corrugated diaphragms, which may be used as separating diaphragms with low thermal resistance, can be realized. In contrast to the fabrication of these diaphragms with a highly doped etch-stop (11), here the fabrication can be carried out in a single process step, and induces no mechanical stresses in the material. So the thickness of the corrugated diaphragms can be varied within wide limits.

Micromechanical heat exchangers can be realized with spiral alignment of the grooves on the wafer front and back. The etched structures are encapsulated in this case on both sides by Pyrex plates. Other applications demand structures with very small dimensions on the wafer surface. For the fabrication of an accelerometer where the external mass is used as seismic mass (12), the dimensions required for the total device to a large extent depend on how small the post in the middle can be.

The feasibility of smaller structures paves the way for novel devices. By using only one-half of the compensation structure presented for etching a small square, small rectangular projections can be realized from a structure which otherwise has a straight corner. These structures can be used for the design of a piezoresistive inclination sensor. This kind of sensor requires large, movable masses fastened to bending beams, which should be as long as possible.

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REFERENCES

1. Hommel, "Handbuch gefährlicher Güter," Springer-Verlag, Berlin (1986).
2. H. Seidel, L. Csepregi, A. Heuberger, and H. Baumgärtner, Submitted to *This Journal.*
3. X. Wu and H. K. Wen, Transducers '87, Tokyo (1987).
4. R. A. Buser and N. F. de Rooij, "Monolithisches Kraftsensorfeld," VDI-Berichte, Nr. 677 (1988).
5. E. Obermeier, H. Sandmaier, and K. Kühl, IEEE Workshop on Micro-Robotics and Teleoperators, Hyannis, MA (1987).
6. H. Seidel, Dissertation, FU Berlin (1986).
7. K. E. Bean, *IEEE Trans. Electron. Devices*, **ED-25**, 1185 (1987).
8. B. Puers and W. Sansen, Transducers '89, Montreux (1989).
9. X. Wu and W. A. Ko, Transducers '87, Tokyo (1987).
10. H. Sandmaier, Dissertation, TU München (1988).
11. A. Toth, G. Kerder, S. Sander, and J. Gynlai, Proc. Eurosensors '87, Cambridge (1987).
12. K. Yamada, K. Higuchi, and H. Tamigawa, Transducers '89, Montreux (1989).

Trench Isolation by Selective Epi and CVD Oxide Cap

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ABSTRACT

A dielectric isolation process is described which produces device areas defined by deep vertical trenches. The trenches consist of a triple dielectric sidewall with an open trench bottom, a partial silicon trench fill formed by selective silicon epitaxial growth, and a CVD SiO_2 cap. Conventional bipolar device structures using this isolation scheme exhibited low defect densities. Device yields were improved by choosing a two-step CVD SiO_2 cap process leading to a greater cap planarity than the single-step cap process.

In semiconductor processing, low defect densities have been achieved for silicon devices using recessed oxide isolation (ROI) (1). The recessed oxide isolation occupies a significant amount of space due to the formation of the bird's beak, even if the stack of dielectric layers is optimized prior to the oxidation (2). Thus, for high density applications, it is desirable to replace the recessed oxide isolation by trench isolation using CVD SiO_2 to fill the trench (3). However, trench fill with CVD SiO_2 oxide results in large voids in the trench because of the buildup of CVD SiO_2 at the corners of the trench during CVD SiO_2 deposition (4). The formation of these large voids can be prevented by limiting the CVD SiO_2 fill to shallow trenches (5). For a deep trench, a structure like a shallow trench can be obtained by performing a partial, selective, silicon epitaxial trench fill initially, and subsequently filling the space above the silicon with CVD oxide (6). Using the latter isolation scheme, a comparison of the defect densities between recessed oxide isolation and trench isolation is reported here.

Experimental

A conventional semiconductor process was utilized to form a bipolar transistor (1). A 2 μm thick epitaxial layer was grown over a buried arsenic ion implanted subcollector. After the boron-doped base area was formed, an arsenic emitter was implanted having a junction depth of 0.5 μm. The resulting base width was 0.25 μm. Phosphorus was diffused from $POCl_3$ to provide a low resistance path between the buried subcollector and subcollector contact. The contacts were formed using platinum silicide and aluminum metallurgy. The isolation was introduced prior to forming the subcollector contact and the base and emitter diffusions.

A test site consisting of transistor chains and discrete transistors was used to evaluate the trench isolation. The mask consisted of a 0.29 μm thick thermal SiO_2 layer, a 0.16 μm thick CVD Si_3N_4 layer and a 0.6 μm thick CVD SiO_2 layer structure. The trenches were etched to a depth of 6 μm by RIE in SF_6 and Cl_2 (7) through a 2.2 μm wide opening in the dielectric films. The trench sidewall consisted of a 50 nm thermal SiO_2, 50 nm CVD Si_3N_4, and 300 nm CVD SiO_2 densified at 950°C for 30 min in steam. After the opening of the trench bottom by RIE in CF_4, epitaxial silicon was grown selectively up to a thickness of 4-5 μm as shown in Fig. 1. The epitaxial silicon was grown at 1000°C using a combination of gases including $SiCl_4$, H_2, HCl, and B_2H_6 (8). The silicon was doped with boron to prevent charge inversion at the bottom of the trench. After filling the trench with silicon, the upper portion of the 300 nm thick CVD SiO_2 sidewall layer was removed in 7:1 BHF. Then, a 50 nm thick CVD Si_3N_4 layer was deposited to seal the trench sidewall and the silicon trench fill prior to depositing 1.5 μm CVD TEOS SiO_2. The oxide was deposited at 720°C in TEOS/N_2 at a pressure of 0.45 torr. This provided the oxide

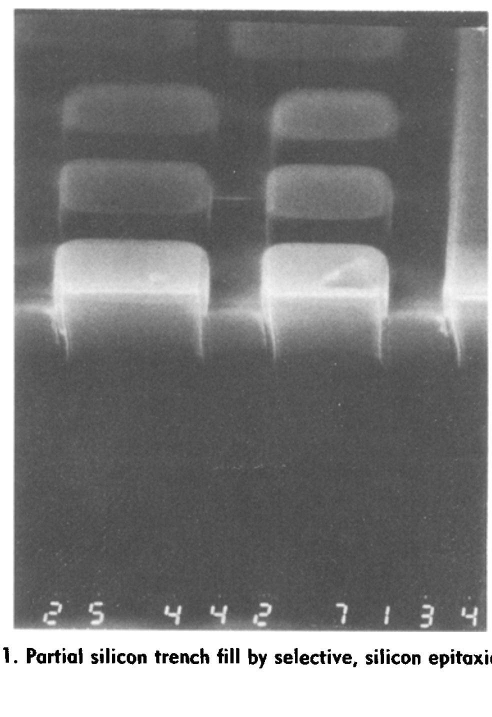

Fig. 1. Partial silicon trench fill by selective, silicon epitaxial deposition.