A multi-step silicon etching process has been developed to fabricate silicon-based terahertz (THz) waveguide components. This technique provides precise dimensional control across multiple etch depths with batch processing capabilities. Nonlinear and passive components such as mixers and multipliers, waveguides, hybrids, OMTs and twists have been fabricated and integrated into a small silicon package. This fabrication technique enables a wafer-stacking architecture to provide ultra-compact multi-pixel receiver front-ends in the THz range.

18 Claims, 6 Drawing Sheets
OTHER PUBLICATIONS


* cited by examiner
THE INVENTION

This application claims priority to and the benefit of U.S. provisional patent application Ser. No. 61/812,097, filed Apr. 15, 2013, which application is incorporated herein by reference in its entirety.

STANDARD REGARDING FEDERALLY
FUNDED RESEARCH OR DEVELOPMENT

The invention described herein was made in the performance of work under a NASA contract, and is subject to the provisions of Public Law 96-517 (35 USC 202) in which the Contractor has elected to retain title.

THE NAMES OF THE PARTIES TO A JOINT
RESEARCH AGREEMENT

Not applicable.

INCORPORATION-BY-REFERENCE OF
MATERIAL SUBMITTED ON A COMPACT
DISC

Not applicable.

FIELD OF THE INVENTION

The invention relates to silicon wafer fabrication methods in general and particularly to fabrication methods that employ deep reactive ion etching (DRIE).

BACKGROUND OF THE INVENTION

THz instruments are being proposed as highly sensitive instruments for the remote sensing of planetary atmospheres on Mars, Venus, Jupiter, Saturn and Saturn’s moon Titan. For these long-term planetary missions, severe constraints are put on the mass and power budget for the payload instruments. See for example V. M. Lubecke, K. Mizuno, G. M. Rebeiz, “Micromachining for terahertz applications”, IEEE-MTT, pp. 1821-1831, 1998. Conventional approaches which package the receiver components in CNC machined metal waveguide blocks are too massive and expensive for multi-pixel instruments that fit within these tight budgets.

Several different micromachining techniques exist for fabrication of terahertz circuits. One process forms the waveguide and device structures directly from permanent resists such as SU-8, as is described in J. Stancee and N. Barker, “Fabrication and integration of micromachined submillimeter-wave circuits,” Microwave and Wireless Components Letters, IEEE, vol. 21, no. 8, pp. 409-411, August 2011. This technique, while requiring a minimum of processing tools, suffers from significant process instabilities and delamination issues between the thick resist and carrier wafer.


SUMMARY OF THE INVENTION

According to one aspect, the invention features a method of manufacturing a terahertz waveguide circuit element. The method comprises the steps of providing a silicon wafer having a surface; providing a SiO$_2$ layer having an initial thickness on the surface; etching a plurality N of SiO$_2$ patterns in the SiO$_2$ layer, each of the plurality N of SiO$_2$ patterns having a respective thickness representing a respective depth of etching into the silicon wafer, the respective thicknesses being different from one another, where N is an integer greater than one; and repeating a total of N times in succession the two steps of performing an SiO$_2$ etch simultaneously on all of the plurality N of SiO$_2$ patterns to expose a respective region of the surface of the silicon wafer beneath the thinnest remaining one of the plurality N of SiO$_2$ patterns; and performing a silicon etch simultaneously on the silicon wafer below all of the exposed respective regions of the surface of the silicon wafer.

In one embodiment, the step of providing a SiO$_2$ layer on the surface is performed by plasma-enhanced chemical vapor deposition.

In another embodiment, the step of providing a SiO$_2$ layer on the surface is performed by thermal growth of SiO$_2$.

In yet another embodiment, the initial thickness of the SiO$_2$ layer is sufficient to provide a safety margin after the plurality of patterns are etched in the SiO$_2$ layer.

In still another embodiment, the step of performing a SiO$_2$ etch is done using an inductively coupled plasma.

In a further embodiment, the step of performing a silicon etch is done using deep reactive ion etching.

In yet a further embodiment, the deep reactive ion etching is performed using SF$_6$.

In an additional embodiment, the deep reactive ion etching is followed by a step comprising exposing the silicon wafer to C$_4$F$_8$ gas.

In one more embodiment, a final etch depth is controlled to within 2% of a depth target.

According to another aspect, the invention relates to a terahertz waveguide circuit element manufactured according to the methods previously enumerated.

In one embodiment, the terahertz waveguide circuit element has a cross section of the waveguide that is rectangular.

In another embodiment, the terahertz waveguide circuit element has a final etch depth that is controlled to within 2% of a depth target.

The foregoing and other objects, aspects, features, and advantages of the invention will become more apparent from the following description and from the claims.

BRIEF DESCRIPTION OF THE DRAWINGS

The objects and features of the invention can be better understood with reference to the drawings described below, and the claims. The drawings are not necessarily to scale,
emphasize instead generally being placed upon illustrating
the principles of the invention. In the drawings, like numerals
are used to indicate like parts throughout the various views.

FIG. 1A is a plan view that illustrates resist spanning on
a wafer.

FIG. 1B is a cross section view of a wafer that illustrates
the resist coverage prior to DRIE using conventional meth-
ods.

FIG. 1C is a cross section view of a wafer that illustrates
the results after DRIE using the resists of FIG. 1B. Due to
thin resist coverage at the edges, the pattern is overetched
(indicated by 102) and holes are etched at the bottom of a
waveguide due to bad resist protection inside an already
etched channel (indicated by 104).

FIG. 2 is an image that shows holes etched at the bottom
of the patterns illustrated in FIG. 3.

FIG. 3 is an image that shows over-etched patterns.

FIG. 4 is an image of the same double-depth pattern as in
FIG. 3 with the addition of a mask of SiO₂. The SiO₂ clearly
provides patterns that are better defined in shape and size.

FIG. 5 is an illustration showing a mask layout of an OMT
design.

FIG. 6 is an image showing extreme over-etching around
the edges of the patterns of the design of FIG. 5 after only
3 etch patterns were processed.

FIG. 7 is a diagram that illustrates a predefined SiO₂
pattern of a waveguide twist.

FIG. 8 is an SEM image of a waveguide twist after
completion of all the etch steps using the multi-step DRIE
process.

FIG. 9 is a diagram that illustrates a predefined SiO₂
pattern of an OMT.

FIG. 10 is an SEM image of an OMT after completion of
all the etch steps using the multi-step DRIE process.

FIG. 11 is an image of a silicon micromachined wave-
guide test feature highlighting the waveguide OMT and
twist.

FIG. 12 is a graph showing the results of insertion loss
measurements vs. frequency for a simulation (curve 1202) a
wafer fabricated using the multi-step DRIE process (curve
1204) and a wafer fabricated using the first process with a
SiO₂ hard mask (curve 1206). The insertion loss shown is
between ports 'a' and 'b' shown in FIG. 11, so the signal
passes through both the OMT and twist.

DETAILED DESCRIPTION

Fabrication Methods

One approach for fabricating highly integrated and com-
 pact submillimeter receiver front-ends is to make all the RF
elements in silicon where the power amplifiers, multipliers,
and mixer chips can be integrated in a single silicon micro-
machined block.

We describe semiconductor-based fabrication techniques
that allow the integration of passive and active components
into such a stacked silicon wafer configuration. This archi-
tecture shrinks the heterodyne receiver front-end elements
by an order of magnitude in mass and size compared to
conventional metal milling techniques.

The utilization of micromachined silicon blocks for THz
circuits places a number of important considerations on
these structures. Very smooth etched surfaces are advan-
tageous to minimize ohmic losses in THz frequency wave-
guides and device channels. The cross section of the wave-
guide preferably should be precisely rectangular in order to
minimize scattering from geometric inhomogeneities and to
allow the successful integration of MMIC amplifiers, mul-
tipliers, and mixers.

Initial Fabrication Techniques

We employ silicon Deep Reactive Ion Etching (DRIE), a
technique that we believe offers a wider range of possibilities
in terms of structures, designs and better resolutions that
other methods. DRIE of bulk silicon wafers is a relatively
well-established fabrication technique capable of etching
high aspect ratio features. See for example G. Chattopad-
ion etching based silicon micromachined components at
terahertz frequencies for space applications”, in Infrared,
1-2. It uses the Bosch process based on the alternative
exposures to SF₆ and C₄F₉ gases, in which the SF₆ is used
to etch the silicon, while the C₄F₉ passivates the etched
surfaces. See for example F. Läermer and A. Schilp, Method
of Anisotropic Etching Si, U.S. Pat. No. 5,501,893, issued
Mar. 26, 1996. Since the method is based on etching, this
technique struggles to maintain straight sidewalls, uniform
depths across the wafer for each etch depth and smooth
etched patterns. All of these are important parameters for the
integration of THz waveguide components. Intensive work
has been performed to optimize the etching process param-
eters, previously presented in C. Jung, B. Thomas, C. Lee, A.
Paralta, G. Chattopadhyay, J. Gill, R. Lin, E. Schlecht, K.
Cooper and I. Mehdi, “Compact Submillimeterwave Receiv-
ers made with Semiconductor Nano-Fabrication Technolo-
gies”, IEEE MTT International Microwave Symposium,
Baltimore, Md., USA, June 2011.

We initially used AZ9260 and AZ5214 photoresists (PR)
and UV photolithography defined patterns to test the various
etch process parameters. However, the use of these “soft”
masks proved to be limited when several etch depths were
required within the same wafer. An additional problem is the
etch selectivity between the photoresist and the silicon
which was not always sufficient for etching through the
entire thickness of the wafer.

Therefore, a different kind of patterning mask is needed,
with better selectivity, which allows one to fabricate numer-
ous etch patterns with different depths, all within the same
silicon piece.

When etching using conventional wafer processing, UV
photoresists are commonly used as patterning masks. They
are deposited on a wafer using a spinning technique, pro-
viding a perfectly uniform surface on a flat, non-processed
wafer. Each pattern is individually etched to its depth target
and the mask is removed with solvents. This process is then
repeated until all the patterns are fabricated.

However, after two or more deep etches are performed,
the wafer is in general not sufficiently flat to achieve uniform
photoresist coverage. The resist becomes very thin at the
edge of an etched channel, getting even thinner for patterns
on the outer side of the wafer as the amount of resist
available decreases, and the mask will not be homogeneous
at the bottom of the channel, as shown in FIG. 1B. If the
resist is too thin at the edge or does not cover the bottom
surface of a previously etched pattern, undesired areas will
be exposed and etched. FIG. 1C illustrates these problems
with a diagram.

FIG. 2 is an image that shows holes etched at the bottom
of the patterns illustrated in FIG. 3.

FIG. 3 is an image that shows over-etched patterns.

Addition of SiO₂ as a Hard Mask

To solve the problem of the thin photoresist at the edge of
the etched patterns, we deposit silicon dioxide (SiO₂) as an
PECVD deposited SiO₂ films. As an illustration, FIG. 6

lems such as overheating of the photoresist during the ICP

40 µm, and so forth. Every pattern is gradually etched

to their final depth target.

We use only SiO₂ as the hard mask. Instead of etching

photoresist, followed by etching with a fluorine-based inductively
coupled plasma (ICP) to expose the silicon.

This additional hard mask proves to be very precise for
controlling the size and shape of a pattern, avoiding the
overetching previously observed. The results are presented in
FIG. 4. FIG. 4 is an image of the same double-depth
pattern as in FIG. 3 with the addition of a mask of SiO₂. The
SiO₂ clearly provides patterns that are better defined in
shape and size.

However, SiO₂ helps as a protective mask only for a small
number of etch depths. When working with 3 or more etch
depths, the resist coverage degenerates to the point where
the SiO₂ cannot compensate for the poor resist edge cover-
age. Using thicker layers of SiO₂ creates additional prob-

lems such as overheating of the photoresist during the ICP
etch and excessive residual stress causing delamination of
PECVD deposited SiO₂ films. As an illustration, FIG. 6
presents the SEM picture of a 6-depth OMT design (see for
example A. Dunning, S. Srikanth and A. R. Kerr, “A Simple
Orthomode Transducer for Centimeter to Submillimeter
Wavelengths”, International Symposium on Space Terahertz
Technology, ISSTT 2009), with extreme over-etching prob-
lems despite a thick SiO₂ protective mask of 4 µm.

Moreover, as the SiO₂ is only present on the top surface
of the wafer, it does not solve the resist coverage issue at the
bottom of an etched pattern. Therefore, the process in which
each pattern was individually etched to its desired depth
would not work for the fabrication of complicated THz
circuits.

Multi-Step DRIE Process

In the new fabrication process, we avoid the use of
photoresist in DRIE. This solves the through-wafer etch
issue. We use only SiO₂ as the hard mask. Instead of etching
each pattern individually to its desired depth, we etch only
the depth difference between each pattern, as presented in
Table 1. For example, rather than etching, 200 µm then 150
µm, 105 µm and so on, we will only etch 50 µm, then 45 µm,
then 40 µm, and so forth. Every pattern is gradually etched
down with the next one until all the patterns are completed
to their final depth target.

TABLE 1

Example for 5-etch pattern, where each depth difference is highlighted
by underlining.

<table>
<thead>
<tr>
<th>Depth</th>
<th>SIO2 Thickness</th>
</tr>
</thead>
<tbody>
<tr>
<td>200</td>
<td>340 nm</td>
</tr>
<tr>
<td>150</td>
<td>200</td>
</tr>
<tr>
<td>105</td>
<td>135</td>
</tr>
<tr>
<td>60</td>
<td>85</td>
</tr>
<tr>
<td>20</td>
<td>65</td>
</tr>
</tbody>
</table>

Prior any DRIE etching, each etch depth pattern is masked
by UV photolithography. Using the DRIE recipe SiO₂/Si
selectivity and the depth difference between each step, the
thickness of SiO₂ needed for each pattern can be calculated,
as presented in Table 1. As a protection margin of safety, an
addition 10-20 µm is added to these numbers in case the
selectivity in DRIE fluctuates. The SiO₂ is etched in ICP,
with a ~70 nm/min etch rate to ensure precise control over
the final thickness. Once all the SiO₂ steps are defined, the
first pattern in etched down to the silicon and the DRIE
etching can begin. It should be noted that by defining the
patterns in SiO₂ before any DRIE is performed, a thin
photoresist can be used which offers the best resolution
available.

FIG. 7 is a diagram that illustrates a predefined SiO₂
pattern of a waveguide twist.

FIG. 8 is an SEM image of a waveguide twist after
completion of all the etch steps using the multi-step DRIE
process.

FIG. 9 is a diagram that illustrates a predefined SiO₂
pattern of an OMT. Each segment represents a DRIE etch
depth, defined by a specific SiO₂ thickness.

FIG. 10 is an SEM image of an OMT after completion of
all the etch steps using the multi-step DRIE process.

Testing Results

While working on the process optimization, various tests
features were fabricated to validate each development step.
Straight waveguide sections measured show losses com-
parable to metal machined waveguides. At WR-1.5 (500 to 750
GHz) losses were measured at 0.1-0.08 dB/mm. See T. Reck,
C. Jung-Kubiak, J. Gill, and G. Chattopadhyay, “Measure-
ment of silicon micromachined waveguide components at
500 to 750 GHz”, IEEE Transactions on Terahertz Science

We also recently reported our work on waveguide filters
at frequencies covering the entire WR-1.5 band fabricated
using this technique. See C. A. Leal-Sevillano, T. Reck, C.
Jung-Kubiak, G. Chattopadhyay, J. A. Ruiz-Cruz, J. R.
Montejo-Garai, and J. M. Rebollar, “Silicon Micromachined
Canonical E-Plane and H-Plane Bandpass Filters at the
Terahertz Band”, IEE Microwave and Wireless Components

These structures only tested single etch depth devices, so
to characterize the electromagnetic performance of the mul-
tietch step process a significantly more complex device is
chosen, the series connection of the waveguide polarization
twist shown in FIG. 8 and the orthomode transducer (OMT)
shown in FIG. 10. FIG. 11 shows the OMT and twist test
device.

FIG. 12 shows measurements results comparing the initial
hard mask process to the final multi-step etch process. The
insertion loss, or the power lost through the device, is
appreciably improved with the use of the multi-etch step
process. This improvement is believed to come from a
reduction in waveguide loss by the elimination of the over-etching produced by poor resist coverage. In addition, the waveguide circuit couples more efficiently since the multi-step etch process provides improved patterning accuracy.

This multi-step DRIE process has also been demonstrated in high frequency circuits where the use conventional machining techniques is not possible, due to the very fine structures needed. We recently demonstrated a 2.55 THz waveguide HEB mixer block, with a DSB receiver noise temperature of $T_{\mathrm{rec}}^{\mathrm{DSB}}$ of 2000±100 K (Y-factor of 1.09±0.005). See Faouzi Boussaha, Jonathan Kawamura, Jeffery Stern, Cecile Jung, Anders Skalare, and Victor White, “Terahertz-frequency Waveguide HEB Mixers for Spectral Line Astronomy,” Proceedings of SPIE Conference on Telescopes and Astronomical Instrumentation, Amsterdam-Netherlands, July 2012.

We have described a fabrication process for silicon-based terahertz (THz) waveguide components. This technique uses a predefined SiO$_2$ hard mask and a DRIE etching process, in which the difference between each pattern is etched, to gradually form a complex multi-depth structure. This technique provides precise dimensional control across multiple etch depths with batch processing capabilities. Nonlinear and passive components such as mixers and multipliers waveguides, hybrids, OMTs and twists have been fabricated and integrated into a small silicon package. This fabrication technique enables a wafer-stacking architecture to provide ultra-compact multi-pixel receiver front-ends in the THz range. The fabricated silicon parts are extremely well defined and the final etch depths are controlled to within 2% of a depth target. Tests validate the use of silicon for THz circuits as a batch-process alternative to conventional metal machining, enabling large pixel count ultra-compact receiver architectures.

DEFINITIONS

Unless otherwise explicitly recited herein, any reference to an electronic signal or an electromagnetic signal (or their equivalents) is to be understood as referring to a non-transitory electronic signal or a non-transitory electromagnetic signal.

Any patent, patent application, patent application publication, journal article, book, published paper, or other publicly available material identified in the specification is hereby incorporated by reference herein in its entirety. Any material, or portion thereof, that is said to be incorporated by reference herein, but which conflicts with existing definitions, statements, or other disclosure material explicitly set forth herein is only incorporated to the extent that no conflict arises between that incorporated material and the present disclosure material. In the event of a conflict, the conflict is to be resolved in favor of the present disclosure as the preferred disclosure.

While the present invention has been particularly shown and described with reference to the preferred mode as illustrated in the drawing, it will be understood by one skilled in the art that various changes in detail may be affected therein without departing from the spirit and scope of the invention as defined by the claims.

What is claimed is:

1. A method of manufacturing a silicon waveguide circuit element, comprising the steps of:
   providing a silicon wafer having a surface comprising a flat surface;
   providing a SiO$_2$ layer having an initial thickness on said surface;
   etching a plurality N of patterns in said SiO$_2$ layer, to form a plurality N of SiO$_2$ patterns having a respective thickness representing a respective depth of etching into said silicon wafer, said respective thicknesses being different from one another, where N is an integer greater than one; and
   repeating a total of N times in succession the two steps of:
   (1) performing an SiO$_2$ etch simultaneously on all of said plurality N of SiO$_2$ patterns to expose said surface of said plurality N of SiO$_2$ patterns;
   (2) performing a silicon etch simultaneously on said silicon wafer below said plurality N of SiO$_2$ patterns to form a plurality N of SiO$_2$ patterns having a respective depth associated with a next thinnest remaining one of said plurality N of SiO$_2$ patterns;
   wherein:
   each of said plurality N of patterns are etched down into said silicon wafer to their respective depth of etching, and a multi depth structure in said silicon wafer is formed.

2. The method of manufacturing said silicon waveguide circuit element of claim 1, wherein the step of providing said SiO$_2$ layer on said surface is performed by plasma-enhanced chemical vapor deposition.

3. The method of manufacturing said silicon waveguide circuit element of claim 1, wherein the step of providing said SiO$_2$ layer on said surface is performed by thermal growth of SiO$_2$.

4. The method of manufacturing said silicon waveguide circuit element of claim 1, wherein said initial thickness of said SiO$_2$ layer is sufficient to provide a safety margin after said plurality N of patterns are etched in said SiO$_2$ layer.

5. The method of manufacturing said silicon waveguide circuit element of claim 1, wherein said depth etching is done using an inductively coupled plasma.

6. The method of manufacturing said silicon waveguide circuit element of claim 1, wherein said step of performing said silicon etch is done using deep reactive ion etching.

7. The method of manufacturing said silicon waveguide circuit element of claim 1, wherein said step of performing said silicon etch is done using deep reactive ion etching is followed by a step comprising exposing said silicon wafer to C$_4$F$_8$ gas.

8. The method of manufacturing said silicon waveguide circuit element of claim 1, wherein said multi depth structure includes a cross section of a waveguide that is rectangular.

9. The method of manufacturing said silicon waveguide circuit element of claim 1, wherein said respective depths etched into said silicon wafer are controlled to within 2% of depth targets for said respective depths.

10. The method of claim 1, wherein said silicon waveguide circuit element is a terahertz silicon waveguide circuit element comprising said multi depth structure.

11. The method of claim 10, wherein said multi depth structure includes a cross section of a waveguide that is rectangular.

12. The method of claim 1, wherein:
   for the first repeating of said two steps, said thinnest remaining one of said plurality N of SiO$_2$ patterns has
said respective thickness representing a deepest of said respective depths of etching into said silicon wafer, and for the final repeating of said two steps, said thinnest remaining one of said plurality N of SiO₂ patterns has said respective thickness representing a shallowest of said respective depths of etching into said silicon wafer.

13. A method of fabricating a silicon waveguide component, comprising:

providing at least one mask on silicon, the at least one mask including a plurality N of patterns, the patterns each:

- associated with a different thickness of the mask designed to achieve a different depth of etching into the silicon, where N is an integer; and
- indexed with an integer j, wherein 1 ≤ j ≤ N and the jᵗʰ pattern is designed to achieve a deeper depth of etching than the j+1ᵗʰ pattern;

performing N etch steps each indexed with an integer k, wherein:

1 ≤ k ≤ N and the etch steps are performed in order of increasing k, and

during the kᵗʰ etch step, the silicon is etched with all the one or more jᵗʰ patterns, wherein j ≤ k, by a depth comprising a difference between the depth associated with the jᵗʰ pattern wherein j ≤ k and the depth associated with the jᵗʰ pattern wherein j = k+1; and wherein each pattern is etched down into the silicon such that the jᵗʰ pattern is etched down to the depth associated with the jᵗʰ pattern and the waveguide component comprising a multi depth structure in the silicon is formed.

14. The method of claim 13, wherein the silicon is etched using deep reactive ion etching.

15. The method of claim 13, wherein the silicon waveguide component is a silicon terahertz waveguide.

16. The method of claim 15, wherein the silicon terahertz waveguide waveguide has an insertion loss that is decreased as compared to insertion loss for a silicon terahertz waveguide fabricated using a process wherein structures in the silicon terahertz waveguide are etched to their final depth in the silicon in a single etch step.

17. The method of claim 15, wherein the silicon terahertz waveguide hosts a mixer.

18. A method of fabricating a silicon waveguide component, comprising:

providing a mask including a plurality of patterns; gradually etching the plurality of the patterns into silicon using a plurality of etch steps, wherein:

- the patterns are each etched to an etch depth in the silicon; the patterns are etched in a succession starting with the pattern being etched to a deepest etch depth and ending with the pattern being etched to a shallowest etch depth and such that each of the patterns are etched down with a next one of the patterns, and each etch step etches a depth difference between the patterns until all the patterns are etched to their etch depth.