Monolithic coupling of a SU8 waveguide to a silicon photodiode

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We present quantitative results of light coupling from SU8 waveguides into silicon p-n photodiodes in monolithically integrated structures. Multimode, 12 μm thick, and 20 μm wide SU8 waveguides were fabricated to overlap 40×180 μm² photodiodes, with three different waveguide-photodiode overlap lengths. The attenuation due to leaky-mode coupling in the overlap area was then calculated from photocurrent measurements. The overlap attenuation ranged from a minimum of 2.2 dB per mm overlap length to a maximum of about 3 dB/mm, comparing favorably with reported nonpolymeric waveguide-Si photodiode attenuations.

The monolithic integration of waveguides and photodiodes is one of the outstanding technical challenges in silicon micro-optoelectromechanical systems (MOEMS). Most waveguide-photodiode integration studies in literature concentrate on nonpolymeric waveguides and detectors fabricated in III–V substrates.1,2 On silicon substrates, a limited number of reported studies approached the problem by using silicon-based waveguides, i.e., silicon oxides or silicon oxinitrides (SiON), with or without antiresonant (AR) elements. Thus, Baba and Kokubun3 coupled an AR reflecting optical waveguide (ARROW) with a SiO₂ core to a silicon p-n photodiode, achieving overlap region attenuations of up to 27 dB per mm overlap length with an AR coating, and 1 dB/mm without an AR coating. We will henceforth use “dB/mm” as an “overlap attenuation” figure of merit. Kapser and Deimel4 coupled 850 nm light through SiON waveguides with an AR coating to lateral p-i-n Si photodiodes. The coupling was characterized by absorption coefficients (equivalent to overlap attenuations) of 5.4 dB/mm for the transverse electric mode, and 4.3 dB/mm for the transverse magnetic mode. Wunderlich et al.5 investigated two methods for coupling integral optical SiON waveguides to lateral p-i-n photodiodes: end fire and leaky wave (referred to hereafter as “leaky mode”). The leaky mode reflects the coupling of the evanescent field of the light in the waveguide into the semiconductor. Along an overlap length x, optical energy is deprived of the waveguide continuously, following a function \( P(x) = P_0 \times (1 - e^{-αx}) \), where \( P_0 \) is the energy in the waveguide at the leading edge (\( x = 0 \)) of the photodiode, and \( α \) is the absorption coefficient of the photodiode.5 Wunderlich et al.5 reported a leaky-mode coupling efficiency of about 1.4 dB/mm at 633 nm. Benaissa et al.6 reported 0.7–1.3 dB/mm leaky-mode attenuations of coupled SiO₂ ARROWS with silicon p-n photodiodes at 633 nm. One can see that without AR coatings, the leaky-mode attenuation for nonpolymeric waveguide-Si photodiode coupling is quite weak, in the 1–1.5 dB/mm range.

Very few studies have dealt with the coupling of polymeric waveguides and photodiodes. A very recent one, by Borges et al.7 describes the design of optical biosensors involving a polymeric ARROW coupled to a metal–semiconductor–metal detector on GaAs. The coupling between waveguide and photodiode is leaky mode, however, no overlap attenuation figures are given. SU8 is a recently developed negative photoresist,8 which can be built to very high (hundreds of microns) thicknesses, and therefore amenable for use in very high-aspect ratio (thickness-to-width) structures in microelectromechanical systems (MEMS) technologies. Waveguides formed of SU8 would be inherently process compatible with silicon MEMS structures. In literature, there is practically no information on SU8 waveguide-Si photodiode couplings.

Integrated multimode SU8 waveguide-p-n photodiode structures were fabricated on Si (100) wafers. A typical integrated structure is shown schematically in cross section in Fig. 1(a). First, 40×180 μm² area photodiodes were fabricated in the silicon wafer. The junction depth was chosen such that the absorption quantum efficiency in the range of 633–850 nm was maximal. A 0.3 μm thick polysilicon layer was deposited over the entire wafer prior to junction formation. Its subsequent oxidation as well as additional process steps involving the substrate left a 1 μm thick, localized oxidation of Si (LOCOS)-type field oxide “isolation layer” everywhere except in the overlap area, where a thin doped polysilicon layer remained as a top contact to the photodiode. SU8 rib waveguides of a few mm length and with a cross section of 12 μm (thickness) × 20 μm (width) were then fabricated on top of the oxide. The LOCOS process created a bird’s beak at the edge of the photodiode. In order to measure the overlap attenuation, three different overlap length configurations with the photodiode were fabricated. Top views of these are shown schematically in Fig. 1(b).
configuration A, the waveguide ends at the leading edge of
the photodiode area (zero overlap); in configuration B, the
waveguide and the photodiode overlap over ~42 μm (me-
dium overlap); in configuration C, the overlap length is
~126 μm (maximum overlap). An optical micrograph of a
“chip” containing a number of integrated waveguide-
photodiode structures is shown in Fig. 2. The light source in
all experiments was an external 633 nm AlGaInP diode laser with a nominal output of 1 mW, pig-
tailed to a single mode fiber. The fiber was coupled into the
SU8 waveguide through a focusing lens (f = 11 mm). The
power coupled from the laser into the waveguide, \( P_L \), was
measured by placing a calibrated detector at the waveguide
edge plane, and was found to vary between 0.18 and 0.27
mW.

The fabrication of the SU8 waveguides is now described
briefly. A back side photodiode metallization consisting of
200 Å Cr followed by 2000 Å Au was formed on each chip, to
avoid post-SU8 process high-temperature steps. SU8/
SM1070 (SOTEC Corp.) was spun coated on the chip at 4500
rpm for 40 s, with a speed ramp of 500 rpm/s. The SU8 was
then prebaked at 95 °C for 15 min, exposed in a Karl Suss
MA6 mask aligner for a total of 100 s (four exposures of 25
s each, with 60 s intervals), then baked again at 95 °C for 15
min, and developed for 3 min in a fresh SMPA photoepoxy
developer (SOTEC Corp.). Finally, the developed SU8
waveguides were postbaked/hardened starting at 95 °C,
ramped for 10 min to 200 °C, and held for an additional 15
min at 200 °C. The refractive index of the SU8 layer, as
determined with a Woollam M-2000D ellipsometer, was
1.65.

Electrical current–voltage (\( I−V \)) characterizations in the
dark and under illumination were performed on the photo-
diodes both prior to (at the wafer level) and after waveguide
fabrication (at the chip level) using a standard \( I−V \) probe
station. The photodiode responsivity “\( R \)” was measured by
directly illuminating the photodiode through the small core
(4 μm) single mode optical fiber, and by comparing the mea-
sured photocurrent with that of a well characterized, cali-
brated photodiode. \( R \) was found to be 0.33 A/W. The photo-
diode photocurrent was measured at a reverse bias of 0.2 V
and the detected power was calculated by multiplying the
measured photocurrent by \( R \). Several measurements were

carried out for configurations B and C while masking the
waveguide edge, in order to eliminate direct illumination into
the photodiode. In every measurement, an appropriate align-
ment calibration was performed to determine the optimal
lamp positioning relative to the waveguide, in order to obtain
a maximal photodiode reading. The best fiber–waveguide
coupling was obtained with a cleaved SU8 waveguide edge.

The final objective of this study was to estimate the SU8
waveguide–Si photodiode coupling efficiency in the form of
overlap attenuation. This requires knowledge of the power
radiated by the leaky-mode coupling into the photodiode,
\( P_{rad} \), as shown in Fig. 3. The power coupled into the wave-
guide is \( P_L \) multiplied by the transmission factor \( T \), the latter
calculated to be 0.75 from the respective refractive indices of
air and SU8. The waveguide attenuation, \( WG_{att} \), was calcu-
lated by measuring the scattered energy at various points
along the waveguide. This was done for several waveguides

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**FIG. 1.** Integrated SU8 waveguide-Si photodetector structure: (a) Schematic
cross section, and (b) schematic top view.

**FIG. 2.** Top view of chip with integrated waveguide-photodiode structures.

**FIG. 3.** Schematic cross section of integrated structure showing the various
calculated and measured entities.
TABLE I. Summary of results, including calculated overlap attenuations.

<table>
<thead>
<tr>
<th>Waveguide No.</th>
<th>Configuration</th>
<th>$P_L$ (mW)</th>
<th>$T$</th>
<th>$WG_{\text{att}}$</th>
<th>$P_0$ (mW)</th>
<th>$P_{\text{rad}}$ (mW)</th>
<th>$E_{ff}$</th>
<th>Overlap attenuation (dB/mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>B</td>
<td>0.27</td>
<td>0.75</td>
<td>0.1699</td>
<td>0.0344</td>
<td>0.0010</td>
<td>0.029</td>
<td>3.05</td>
</tr>
<tr>
<td>2</td>
<td>C</td>
<td>0.18</td>
<td>0.75</td>
<td>0.1195</td>
<td>0.0161</td>
<td>0.0012</td>
<td>0.076</td>
<td>2.67</td>
</tr>
<tr>
<td>3</td>
<td>C</td>
<td>0.18</td>
<td>0.75</td>
<td>0.1540</td>
<td>0.0208</td>
<td>0.0013</td>
<td>0.060</td>
<td>2.22</td>
</tr>
<tr>
<td>4</td>
<td>C</td>
<td>0.26</td>
<td>0.75</td>
<td>0.1540</td>
<td>0.0300</td>
<td>0.0020</td>
<td>0.066</td>
<td>2.38</td>
</tr>
</tbody>
</table>

In common with the geometry of Ref. 5, there is a "bird’s beak" structure at the edge of the photodiode, formed in the LOCOS fabrication process. As shown in Ref. 5, in some cases, this structure may improve the coupling. As seen in the cross section of Fig. 1(a), the SU8 waveguide is also naturally bent into the photodiode area, forming a tapered structure, which probably further enhances the coupling. Sidewall scattering and substrate roughness, although reducing waveguide quality, increase the coupling efficiency due to additional scattering into the photodiode.

In summary, we present quantitative measurements of SU8 waveguide-Si photodiode integrated structures. One of the major advantages of the SU8, it being a photore sist, is its easy process and the great flexibility in varying the thickness from submicron to hundreds of microns. This is particularly advantageous in MOEMS processing, e.g., when the SU8 serves also as a mechanical element material. Our results indicate that good coupling efficiencies can be achieved without the complicated processes involved in ARROW structures.

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FIG. 4. Measured power at various points along a waveguide, and calculated waveguide attenuation.