Submicron modulation-doped field-effect transistor/metal-semiconductor-metal-based optoelectronic integrated circuit receiver fabricated by direct-write electron-beam lithography


Center for Compound Semiconductor Microelectronics and Department of Electrical and Computer Engineering, University of Illinois at Urbana-Champaign, Urbana, Illinois 61801

(Received 26 May 1992; accepted 30 July 1992)

An all direct-write electron-beam fabrication process has been developed for the fabrication of monolithic optoelectronic integrated circuits (OEICs). Various electron-beam resist technologies are investigated including image reversed AZ5214, PMMA/P[MMA—MAA] bilayer, and PMMA/P[MMA—MAA]/PMMA trilayer. A novel single-step air-bridge formation process utilizing selective development is described. These processes are demonstrated in the fabrication of a 0.85-μm sensitive OEIC receiver comprised of a metal–semiconductor–metal (MSM) detector integrated with a submicron GaAs/InGaAs/AlGaAs pseudomorphic modulation-doped field-effect transistor based transimpedance amplifier. A 3-dB transimpedance bandwidth of 5.6 GHz and a transimpedance bandwidth product of 4.8 THz Ω are measured for the amplifier. Discrete high-resolution MSM photodetectors with finger/gap spacings ranging from 0.1 to 1.0 μm have been fabricated and characterized.

I. INTRODUCTION

As the processing speed of computer chips increases, the bandwidth of interchip connections must likewise increase. Present electrical computer interconnects are hard pressed to break the 1-GHz mark. Optical interconnects, however, hold the promise of essentially an unlimited bandwidth. A key component of any optical interconnection scheme is the lightwave receiver which consists of a photodetector and an electrical preamplifier. The large numbers of low-cost optical data channels required by high-speed very large scale integrated (VLSI) chips demand that the detector and amplifier be monolithically integrated in a so-called optoelectronic integrated circuit (OEIC). High-performance components, such as short gate-length modulation-doped field-effect transistors (MODFETs) and submicron metal–semiconductor–metal (MSM) photodetectors, can be used to achieve a wide bandwidth OEIC receiver design. To this end, we have developed an all direct-write electron-beam fabrication process for the fabrication of 0.85-μm wavelength sensitive photoreceivers. The receivers are based on an MSM photodetector and a submicron GaAs/InGaAs/AlGaAs pseudomorphic MODFET transimpedance amplifier.

The process flow for OEIC fabrication is shown in Fig. 1. Only the initial fiducial level uses photolithography; all other layers use direct-write e-beam lithography. Although the throughput of e-beam lithography has limited its use in the production environment, its “programmable” nature and high resolution are ideal for the research environment. Circuits are fabricated using a two-level metal process with mesa isolation, quarter-micron T gates, and SiN= dielectric passivation/antireflection (AR) coating. A third level of metal is also possible using a novel direct-write air-bridge process to be described.

II. ELECTRON-BEAM FABRICATION

All exposures are performed on a Cambridge Instruments (Leica) EBMF 10.5 at either 30 or 40 keV and at a 1.6384-mm field size. All pattern levels are aligned relative to the fiducial level. Four alignment marks are located on the meridians of a 1.6 X 1.6-mm die and are used to adjust for shift, rotation, and scaling of the exposure field. The fiducial level also uniquely numbers each die so that if needed, the exact die location can be manually determined at write time. Die labeling is found to be very useful, especially for odd-sized wafer pieces.

Various resist technologies are investigated and incorporated into the fabrication process. In general, three different processes are required: (1) a negative resist for mesa isolation etching; (2) an “overhang” resist profile for metal lift-off, and (3) a T-gate resist technology for low-resistance gates. Additionally a direct-write air-bridge process is desired. Table I summarizes the characteristics of the various resist-developer combinations to be described below.

A. Mesa process

A direct-write negative resist process is needed for field-effect transistor (FET) mesa patterning. Two requirements of the resist are that it must exhibit good adhesion during wet chemical isolation etching (acidic etchants) and it must easily strip without leaving any surface film. The latter requirement is especially important for MODFET fabrication where surface cleanliness is critical for both ohmic and gate contact formation; and where long oxygen plasma cleaning steps are detrimental to the electrical characteristics of the thin epitaxial layers. For a number of years, we have been using image-reversed diazo resist (AZ1350) as the “negative” resist in e-beam mask-
plate generation with good success. Furthermore, our photolithographic lift-off process uses image-reversed AZ5214 to achieve the undercut resist profile. The former process makes use of the fact that e-beam exposure of diazo-type photoresist in the absence of water (i.e., in a vacuum environment) both converts the photoactive compound (PAC) into an insoluble ester and causes the novolac base resin to crosslink. If the resist is then ultraviolet (UV) flood exposed, the remaining areas are rendered highly soluble, resulting in a tone-reversed image. The latter process makes use of a special resist (AZ5214) which, after exposure, undergoes acid catalyzed crosslinking during a post-exposure bake (PEB) step. This photo-crosslinked AZ5214 resist is readily stripped in acetone, leaving a clean wafer surface. The e-beam crosslinked AZ1350 resist, however, sometimes leaves a surface film, particularly at high exposure doses. In light of the enhanced crosslinking of AZ5214 after a PEB, we investigated e-beam exposed image-reversed AZ5214 for use in the mesa fabrication process.

Resist sensitivities and contrasts are measured both with and without a PEB and as a function of e-beam exposure energy (see Table I and Fig. 2). The AZ5214 is diluted 2:1 with propylene glycol monomethyl ether acetate (PG-MEA) and spun on GaAs substrates to a thickness of 500 nm. Samples are soft baked on a 110°C hot plate for 30 s. Immediately following e-beam exposure, samples to be post-baked are hot-plate baked at 125°C for 30 s. Samples are then UV flood exposed at 180 mJ/cm² (λ = 405 nm). The resist is developed in pre-diluted AZ327 MIF (N = 0.27) developer for 30 s at 21°C. The sensitivity of the image-reversed AZ5214 with a PEB is ~40% less than

![Fig. 1. OEIC fabrication process flow. All levels except the fiducial use direct-write e-beam lithography.](image)

![Fig. 2. Sensitivity characteristics for e-beam exposed image-reversed AZ5214 resist with (solid line) and without (dashed line) a PEB. The ability of acetone to strip the crosslinked resist is also shown. Notice that the non-PEB AZ5214 leaves a thin resist film after stripping for exposure doses greater than ~100 μC/cm².](image)

### Table I. Sensitivity and contrast data for various e-beam resists on GaAs used in OEIC fabrication process.

<table>
<thead>
<tr>
<th>Resist system</th>
<th>Developer (at 21°C)</th>
<th>Time (min)</th>
<th>Beam energy (keV)</th>
<th>Sensitivity (μC/cm²)</th>
<th>Contrast (γ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mesa process</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>AZ5214 without PEB</td>
<td>AZ327</td>
<td>0.5</td>
<td>20/30/40</td>
<td>60/80/99</td>
<td>2.9/2.9/2.7</td>
</tr>
<tr>
<td>AZ5214 with PEB</td>
<td>AZ327</td>
<td>0.5</td>
<td>20/30/40</td>
<td>34/49/62</td>
<td>2.8/2.8/2.6</td>
</tr>
<tr>
<td>Lift-off process</td>
<td>PMMA/[PMMA—MAA] bilayer</td>
<td>MIBK</td>
<td>1</td>
<td>63</td>
<td>5.0</td>
</tr>
<tr>
<td>PMMA/[PMMA—MAA] bilayer</td>
<td>1:1 MIBK:IPA</td>
<td>1</td>
<td>30</td>
<td>74</td>
<td>6.8</td>
</tr>
<tr>
<td>PMMA/[PMMA—MAA] bilayer</td>
<td>1:2 MIBK:IPA</td>
<td>1</td>
<td>30</td>
<td>87</td>
<td>11.7</td>
</tr>
<tr>
<td>PMMA/[PMMA—MAA] bilayer</td>
<td>1:3 MIBK:IPA</td>
<td>1</td>
<td>30</td>
<td>117</td>
<td>12.8</td>
</tr>
<tr>
<td>Trilayer T-gate process</td>
<td>400-nm 950-K PMMA</td>
<td>1:3 MIBK:IPA</td>
<td>1</td>
<td>176</td>
<td>6.1</td>
</tr>
<tr>
<td>400-nm PMMA—MAA</td>
<td>1:3 MIBK:IPA</td>
<td>1</td>
<td>30</td>
<td>63</td>
<td>5.7</td>
</tr>
<tr>
<td>400-nm 50-K PMMA</td>
<td>1:3 MIBK:IPA</td>
<td>1</td>
<td>30</td>
<td>110</td>
<td>5.8</td>
</tr>
<tr>
<td>Single-step air-bridge process</td>
<td>1.6-μm 950-K PMMA</td>
<td>xylene/ethanol</td>
<td>3/3</td>
<td>120/470</td>
<td>5.6/3.9</td>
</tr>
<tr>
<td>1.6-μm PMMA—MAA</td>
<td>xylene/ethanol</td>
<td>3/3</td>
<td>30</td>
<td>880/25</td>
<td>2.6/3.4</td>
</tr>
<tr>
<td>400-nm 50-K PMMA</td>
<td>xylene/ethanol</td>
<td>1/1</td>
<td>30</td>
<td>20/250</td>
<td>2.1/4.3</td>
</tr>
<tr>
<td>Submicron grating process</td>
<td>230-μm 950-K PMMA</td>
<td>1:7 MIBK:IPA</td>
<td>1</td>
<td>277</td>
<td>5.5</td>
</tr>
<tr>
<td>250-μm PMMA</td>
<td>1:7 MIBK:IPA</td>
<td>1</td>
<td>40</td>
<td>253</td>
<td>7.2</td>
</tr>
<tr>
<td>PMMA/PMMA bilayer</td>
<td>1:7 MIBK:IPA</td>
<td>1</td>
<td>40</td>
<td>247</td>
<td>6.2</td>
</tr>
</tbody>
</table>

without a PEB. For example, at 30 keV the sensitivity (50% remain-thickness definition) drops from 80 to 49 $\mu$C/cm$^2$ simply by performing a PEB. The resist contrast, on the other hand, remain approximately constant at around 3.

As expected with diazo-type photoresists, etch tests indicate that resist adhesion and resistance to wet-chemical mesa etching is not a problem. The ease of stripping of the resist is evaluated from the same dose test arrays used to calculate resist sensitivity by dipping the array in acetone at room temperature for 30 s and remeasuring with a surface profiler. Of course, longer and more effective stripping procedures could be used; but the purpose here is to get a relative measure of how easily the crosslinked resist can be removed. Figure 2 shows the normalized resist thickness before and after the acetone dip. Notice that although the resist without a PEB (solid line) appears to rapidly dissolve in acetone at doses less than about 500 $\mu$C/cm$^2$, actually a thin, highly crosslinked surface film remains until just below 100 $\mu$C/cm$^2$. Therefore, the lower sensitivity of the resist with a PEB (dashed line) not only translates into shorter write times, but also means that a dose range well below that for surface film formation can be used. Although the mesa pattern level does not require high-resolution lithography, this image-reversed mesa resist process has defined lines as small as 100 nm.

**B. Lift-off process**

A common technique for creating the undercut or overhang resist profile required for reliable metal lift-off is with a double-layer resist system. The bottom layer of resist is chosen to be more sensitive (i.e., develops faster) than the top layer of resist thereby naturally creating an undercut profile. This sensitivity difference can be achieved by using a high molecular weight poly(methylmethacrylate) (PMMA) resist above either a low molecular weight PMMA layer or a sensitive PMMA-MAA copolymer layer. We have adopted the latter approach by using a 400-nm-thick PMMA-MAA (from KTI, 7.5% MAA) bottom layer beneath a 125-nm 950-K PMMA (KTI) top layer. Each layer is individually hot-plate baked for 2 min at 200 °C. Figure 3 shows a scanning electron microscopy (SEM) micrograph of a 2-$\mu$m period grating defined in this PMMA-MAA bilayer resist. The undercut profile is clearly evident. The amount of undercut, which determines the minimum interline spacing, is controlled by both the electron dose and the development process. The effect of these two parameters was studied by exposing a series of 2-$\mu$m period, equal line/space grating structures (identical to an interdigitated MSM) at various doses and then developing each in one of four different developer concentrations of methyl isobutyl ketone (MIBK) and isopropyl alcohol (IPA). Samples are developed for 1 min at 23 °C and rinsed 20 s in IPA. Figure 4 shows the percentage undercut versus the grating duty cycle (0% representing no resist). The 1:3 MIBK:IPA developer exhibits such a deeply undercut profile that it is unable to achieve the desired 50:50 grating. This can be expected because PMMA-MAA is more readily soluble in polar solvents like IPA. Although both the 1:2 and 1:1 developer concentration can define 50:50 gratings, the undercut for the 1:1 may not be sufficient for reliable lift-off. The concentrated MIBK developer is clearly not acceptable, yielding an overcut profile over most of the dose range. Furthermore, resist sensitivity measurements performed on the PMMA-MAA bilayer (see Table I) shows that both the concentrated and 1:1 dilutions of MIBK exhibit markedly lower resist contrast ($\gamma$) compared to the 1:2 and 1:3 developers. Based on these studies, a 1-min development time in 1:2 MIBK:IPA is chosen for the lift-off process.
C. T-gate process

As FET gate lengths are scaled down to submicron dimensions, it is important to minimize the parasitic gate resistance to avoid compromising the improvement in the device's high-frequency and low-noise performance. This has been achieved by adopting a T-gate metal profile to increase the gate cross-sectional area. Although bilayer resist schemes have been used, the trilayer resist technique provides better performance. The total resist thickness is only 130 nm which helps to reduce proximity effects. Furthermore, the sensitivity of the top and bottom layers are more closely matched to limit the extent of resist undercut. The total resist thickness is only 130 nm which helps to reduce proximity effects. The resist structure, from the wafer surface, was chosen: 9

\[ \text{The resist structure, from the wafer surface, was chosen:} \]

\[ \text{9. 150 nm of 950-K PMMA, 400 nm of P[MMA-MAA], and 150 nm of 50-K PMMA.}\]

Gates are exposed at either 30 or 40 keV, 500-pA beam current, and developed 2 min in 1:3 MIBK:IPA. Sensitivities and contrasts for each of these resist layers are shown in Table I. The 50-K PMMA layer provides a good undercut resist profile due to its intermediate sensitivity between that of 950-K PMMA and P[MMA-MAA]. Gate lengths down to about 0.1 \( \mu \text{m} \) are achieved with ~2.5- \( \mu \text{C/cm} \) double-pass line dose and 80- to 100- \( \mu \text{C/cm}^2 \) area sidelobe exposure to slightly widen the top of the T gate.

D. Single-step air-bridge process

A novel air-bridge process has been developed to allow for the formation of air-bridge crossovers in a single exposure and evaporation step. The process relies on the selective development of PMMA and P[MMA-MAA] resists in nonpolar and polar solvents, respectively, as well as the ability of e-beam exposures to individually dose different regions. The resist structure, from the wafer surface, consists of 1.6 \( \mu \text{m} \) of 950-K PMMA, 1 \( \mu \text{m} \) of P[MMA-MAA] (from KTI, 18% MAA), and 0.15 \( \mu \text{m} \) of 50-K PMMA. Air-bridge posts are exposed at 120–140 \( \mu \text{C/cm}^2 \) whereas bridge spans are exposed at only 50–70 \( \mu \text{C/cm}^2 \), both at 30 keV. The development sequence is as follows: (1) 1-min xylene; (2) 3-min ethanol; and (3) 3-min xylene. This leads to gradually sloped post sidewalls for good metal step coverage. The top 50-K PMMA layer provides a slight undercut lip for good lift-off. Figure 5 shows an SEM micrograph of a series of 1.6- \( \mu \text{m} \)-high, 50- \( \mu \text{m} \) span air bridges after evaporation and lift-off of 700 nm of Ti/Au metallization.

E. Submicron Interdigitated gratings

The PMMA/P[MMA-MAA] bilayer lift-off process discussed earlier is limited to grating periods larger than approximately 1.4 \( \mu \text{m} \). Below this period, the undercut and large aspect ratio of the resist makes lithography and lift-off difficult. For high-resolution gratings and MSMs, a thin bilayer of 950-K PMMA on top of 200-K PMMA is used to achieve a small undercut profile. The total resist thickness is only 130 nm which helps to reduce proximity effects. Figure 6 shows a SEM micrograph of a series of 1.6- \( \mu \text{m} \)-high, 50- \( \mu \text{m} \) span air bridges after evaporation and lift-off of 700 nm of Ti/Au metallization.

III. RESULTS

A. OEIC receiver

The OEIC receiver is fabricated on a vertically integrated molecular beam epitaxially (MBE) grown layer structure consisting of a 0.8- \( \mu \text{m} \) undoped GaAs MSM absorption/FET buffer layer, 15-nm undoped In\(_{0.15}\)Ga\(_{0.85}\)As pseudomorphic channel layer, 2-nm undoped Al\(_{0.23}\)Ga\(_{0.77}\)As spacer layer, 40-nm Si doped...
OEICs enhanced chemical-vapor deposition from an optical fiber. Additionally, on-chip MIM bypass capacitors are fabricated using plasma-enhanced chemical-vapor deposition (PECVD) SiN$_x$ ($\sim 15$ pF, 0.2 fF/\mu m$^2$). Figure 7 shows an SEM micrograph of the fabricated receiver.

Quarter-micron pseudomorphic MODFETs exhibiting an $f_T$ and $f_{\max}$ of 66 and 70 GHz, respectively, are utilized in a two-stage trans-impedance amplifier design with an active feedback resistor. The transimpedance is tunable from 300 to 2800 Ω by varying the gate of the common-gate feedback FET from 0 to $-0.8$ V, respectively. A 3-dB transimpedance bandwidth of 5.6 GHz and a transimpedance bandwidth product of 4.8 THz $\Omega$ are measured for the amplifier. This transimpedance bandwidth product is among the highest ever reported for an OEIC receiver. Optical pulse measurements at 850-nm wavelength indicate a bandwidth of $\sim 4.4$ GHz, limited by the large MSM photodetector.

B. Submicron MSM photodetectors

Discrete submicron finger MSMs with $15 \times 15$-\mu m$^2$ area are fabricated with finger/gap widths from 1.0 \mu m down to 0.1 \mu m on 1.5-\mu m-thick undoped MBE grown GaAs. At a constant linear electric field of 10 V/\mu m, typical dark currents range from 300 to 1000 pA. At MSM bias voltages around 2 V, the responsivity is near the theoretical limit of 0.2 A/W for an uncoated MSM. Above this bias, the MSM appears to exhibit slight (less than 2) low-frequency gain. The 50-nm-thick Ti/Au fingers have dc metal resistances ranging from 1 kΩ/mm for the 1-\mu m finger width up to 25 kΩ/mm for the 0.1-\mu m finger width detector. Similarly, the MSM capacitance, as measured at 10 GHz with a network analyzer, starts from about 10 fF for the 1-\mu m finger width, increases rapidly below 0.2 \mu m, and reaches 160 fF for the 0.1-\mu m finger width detector. Based on network analyzer measurements, the 0.1-\mu m finger detector becomes $RC$ limited above about 20 GHz in a 50-Ω system. Wider finger spacings of 0.2 and 0.3 \mu m do not reach the 3-dB $RC$ limit until around 40 and 53 GHz, respectively. Preliminary optical pulse measurements indicate a bandwidth around 10 GHz, limited by a slow tail in the impulse response. The cause of the tail is presently under investigation.

IV. CONCLUSIONS

An all direct-write electron-beam process for the fabrication of OEICs has been developed. Various resist technologies such as image-reversed AZS214, PMMA/PMMA–MAA bilayer, and PMMA/PMMA–MAA/PMMA trilayer have been utilized to achieve a reliable, high-yield process. The process is demonstrated in the fabrication of a quarter-micron pseudomorphic MODFET-based OEIC receiver. The transimpedance amplifier exhibits a 3-dB bandwidth of 5.6 GHz. Additionally, a process for the fabrication of high-resolution, 0.1-\mu m finger MSM photodetectors is outlined and demonstrated.

ACKNOWLEDGMENTS

The authors wish to thank Research Engineer J. Hughes for this technical assistance and Northeast Semiconductor of Ithaca, NY for one of the MBE crystals. This work is supported by the National Science Foundation Grant No. ECD 89-43166. M. Tong is an IBM Resident Study Program Fellow.

---

9Present address: Texas Instruments, Central Research Laboratories, Dallas, TX 75265.
10Present address: IBM, Technology Products Division, Essex Junction, VT 05452.