FIGURE 1. Demonstration of USJ formation using $C_{16}H_{10}/B_{18}H_{22}$ process flow. A) SIMS profiles for Carbon and Boron. B) TEM of amorphous layer thickness formed by the carbon when used as a PAI step.

Demonstration Of Cost-Effective, Highly Productive Ultra-Shallow Junctions Using Molecular Carbon And Boron As An Alternative To Ge/C/B Implantation

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Abstract

In this study we demonstrate a highly productive, cost-effective route to formation of ultra-shallow junctions (USJ) for p-MOS extension implants. Using a modest dose of molecular carbon ($C_{16}H_{10}$) as a pre-amorphizing implant, as well as a diffusion-control "co-implant", we show that the requirement for Ge PAI can be eliminated. This allows a traditional three step process sequence Ge/C/ (B or BF_2) to be replaced with a $C_{16}H_{10}/B_{18}H_{22}$ process. The combination of eliminating the Ge implant (and associated source life degradation well known in Ge implantation), with effective beam current increases for the molecular carbon (30 mA @ 6 keV) and boron (6 mA @ 300 eV), provides a highly productive process alternative. The difference in materials cost is more than offset by the enhanced productivity and reduction of implant steps.

Introduction

- Transistor scaling in the sub-45 nm node has introduced particular challenges to manufacturers [1],[2]
  - formation of ultra-shallow junctions with EC-free, effective boron energies on the order of 400eV – 1 keV
  - Most utilize a pre-amorphization step, typically Ge, and a low energy carbon implant for diffusion control
  - Implementation is difficult:
    - low energies that strain productivity of ion implanters,
    - difficulty in implanting Ge and C, each of which poses a unique set of difficulties for implanters in terms of erosion and source life,
    - cost of raw materials.

Main Thesis

- A scheme for junction formation utilizing molecular carbon and boron, in which the molecular carbon acts as both a pre-amorphizing species and diffusion control co-implant, thereby eliminating the need for Ge[3],[4] is presented

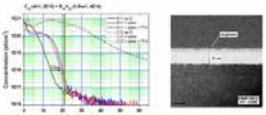


FIGURE 1. Demonstration of USJ formation using $C_{16}H_{10}/B_{18}H_{22}$ process flow. A) SIMS profiles for Carbon and Boron. B) TEM of amorphous layer thickness formed by the carbon when used as a PAI

Outline

- A model is constructed to compare directly a two-step molecular ($C_{16}H_{10}/B_{18}H_{22}$) alternative process to the tradition three-step process sequence Ge/C/ (B or BF_2)
- The model is first used to compare the throughput of the two processes as a function of machine availability
- The model is then used to compare the cost of source materials for these two processes as a function of the molecular materials' cost
- Conclusions are drawn for the comparison which shows the viability of such a molecular alternative
- Finally, the potential process benefits of the molecular alternative are outlined

Concepts of the Model

- Listed in Tables 1 and 2 are the implant conditions considered in this study

Step name	PMOS SDE	PMOS PAI	PMOS Carbon co-implant
Implant species	Boron	Germanium (enriched)	Carbon
Implant beam composition	Monomer Boron	Monomer Germanium	Monomer Carbon
Beam energy (species equiv. keV)	0.5	10	3
Dose (atoms/cm^2)	1.0 e15	5.0 e14	7.0 e14
Beam current (pmA)	11	8	6
Theoretical Max. Throughput (WPH)	116	144	99

Step name	PMOS SDE	PMOS Carbon co-implant
Implant species	Boron	Carbon
Implant beam composition	$B_{18}H_{22}$	$C_{16}H_{10}$
Beam energy (species equiv. keV)	0.5	3
Dose (atoms/cm^2)	1.0 e15	7.0 e14
Beam current (pmA)	15	18
Theoretical Max. Throughput (WPH)	139	180

TABLES 1, 2. Conditions for the Monomer 3 step process and Molecular two step process

Concepts of the Model

- Actual throughputs can be constructed with machine availability (%) and beam tuning time for each recipe, latter assumed the same
- Assumption: new recipe is tuned every 75 wafers (3 Foups)
- Time per Foup in each process is used to determine ratio of throughput
- Note that the beam current for molecular carbon has been restricted since the process step is already at mechanical limit
- Note that the monomer boron beam current is not obtained in drift mode but rather requires decel operation

Germanium Considerations

- Various isotopes of Ge having mass near ^{75}As could lead to cross contamination
- Short of dedicating tool (no As usage), this leads to use of ^{72}Ge and small resolving apertureswhich further restricts beam current
- Naturally occurring ^{72}Ge is low at 20% abundance
- Enriched GeF_4 has double the ^{72}Ge beam current but at significantly increased material cost
- Both enriched and natural GeF_4 are considered in the parametric studies of the model comparison

Use of the Model for Throughput Comparison

- A major variable to be considered when analyzing productivity is the utilization rate or uptime of the implant tool
- Molecular tool requires a periodic source clean which costs about 12% in uptime
- Field data yield average of 67.5% molecular uptime for many months of production (B_{18} usage only) with consecutive months at 75% uptime
- Poor source life with GeF_4 and with CO_2 restrict uptime for monomer alternative
  - Investigate range from 80% to 90% uptime
- Can then fix monomer at 85% uptime and investigate range of molecular from 60% to 75%

Use of the Model for Throughput Comparison

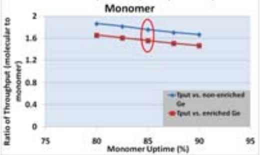


FIGURE 2. Shown is the throughput comparison for the molecular to the monomer tool operation as a ratio against both enriched and non-enriched Ge operation.

Use of the Model for Throughput Comparison

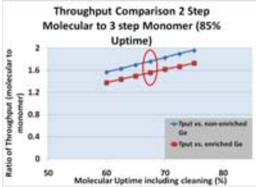


FIGURE 3. Shown is the throughput comparison for the molecular to the monomer tool operation as a ratio against both enriched and non-enriched Ge operation.

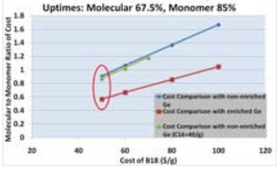
Throughput Comparison Discussion

- The throughput ratio is shown to be more sensitive to the molecular tool uptime, which is a direct result of the tool uptime being lower
- While the nominal throughput ratio is about 1.8X comparing the molecular process to the monomer process with natural Ge, with +/- 0.2 at the ends of range
- Similar trends are shown for enriched Ge material, with all values being ~20% lower

Use of the Model for Materials Cost Comparison

- Neglecting all but source material costs, the model can be used to make the comparison as a function of molecular material costs
- Given the high throughput ratio seen in the last section, this is an underestimate for CoO (e.g. factor of 2 in productivity would mean one less implanter needed with all necessary fixed costs saved)
- Nevertheless, such comparison is useful because it illustrates the strong dependency on the cost of the GeF_4 chosen
  - While manufacturers are using both types of Ge, the price increase is about 3X for a 2X increase in beam current with enriched

Use of the Model for Materials Cost Comparison

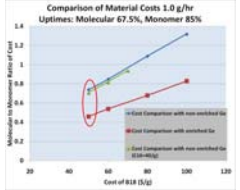


- **FIGURE 4.** Shown is the source materials cost comparison for the molecular to the monomer tool operation as a ratio against both enriched and non-enriched Ge operation.

Materials Cost Comparison Discussion

- The materials cost is at parity with enriched Ge operation even at highest cost of B_{18} and that materials cost goes below parity with non enriched Ge at volume price targets
- A decrease of 20% on the cost of the molecular carbon is shown and this does not have a significant effect
- Source engineering has been underway with the goal of decreasing material consumption relative to field data shown
  - Leaner operation has the double benefit of improving both CoO and throughput enhancement
    - cleaning time is directly proportional to material usage

Use of the Model for Materials Cost Comparison



- **FIGURE 5.** Shown is the source materials cost comparison for the molecular to the monomer tool operation as a ratio against both enriched and non-enriched Ge operation.

Process Implications

- The model provides the capability to perform quantitative analysis of the process performance of the molecular option relative to the conventional monomer process
- The higher mass of the molecules, relative to their monomer counterparts, improves the amorphization of the silicon and eliminates the need for the Ge step
  - Both molecular species show the potential to combine the beneficial effects of a pre-amorphization implant followed by a C and B implant in the formation of ultra-shallow junctions[3]
- The higher beam current of the molecular species increases the dose rate effect of the implants, which has been seen to improve damage engineering[5]

Conclusions

- In all studied cases, utilizing realistic uptimes, the molecular process shows higher productivity and also better cost of ownership vs. enriched Ge
- With source developments that are newly available and volume pricing of the molecular materials, CoO is seen to be 50%-75% of the monomer option regardless of choice of Ge
- This double advantage plus potential process benefits would seem to make the molecular alternative quite attractive for PMOS SDE logic application at future nodes

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