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# High-gain lateral *pn*p bipolar transistors made using focused ion beam implantation

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We report the fabrication of lateral *pn*p bipolar transistors using focused ion beam (FIB) implants of boron and phosphorus for the collector and base, respectively. The implants of  $B^+$ ,  $P^+$ , and  $P^{++}$  were all at a dose of  $1 \times 10^{13}/\text{cm}^2$  and a beam voltage of 75 kV. These implants defined spaces between the emitter and collector regions of 0.5–1.50  $\mu\text{m}$ ; which, after diffusion and zero voltage depletion width effects were considered, produced effective on-wafer device basewidths of  $\sim 0.2 \mu\text{m}$ . For the best devices, values of  $h_{FE}$  near 100 were obtained with good junction characteristics and at peak collector currents of 10  $\mu\text{A}/\mu\text{m}$  of device width.

## I. INTRODUCTION

Focused ion beam (FIB) dopant implants for semiconductor device fabrication have been reported for vertical *npn* bipolar transistors in silicon.<sup>1</sup> Results of these experiments show that devices with the FIB implants of boron (for the base) and arsenic (emitter) performed comparably to those with conventional implants. This indicates that the higher current density FIB implants do not degrade majority or minority carrier transport in the bipolar devices. Because FIB implantation is maskless and has high resolution (FIB widths  $< 0.1 \mu\text{m}$  are now routinely possible), there are important advantages in fabrication of improved device structures. One such advantage was shown with FIB boron-implanted bipolar bases that were profiled laterally in dose to eliminate the Kirk Effect caused by emitter current crowding.<sup>2</sup> With these successful results, we report here an extension in the use of FIB implants of boron and phosphorus to produce lateral *pn*p bipolar transistors with high gain.

High-performance lateral bipolar transistors could be useful for on-chip drivers for metal-oxide-semiconductor (MOS) logic circuits, analog/digital conversion from MOS circuitry (since the lateral bipolar fabrication process is compatible with MOS), or complementary logic circuitry. For example,  $I^2L$  logic is a complementary bipolar structure that is an attractive very large scale integrated (VLSI) candidate because the packing density is very high. In  $I^2L$  logic, the basic logic gate circuit consists of a lateral *pn*p and an inverted vertical *npn* transistor but it has not been utilized widely because the relatively poor performance of the *pn*p slows the entire structure. Several items contribute to the difficulty in making high-performance *pn*p lateral bipolar transistors. First, it is difficult to make the basewidth small enough to provide high-gain and low-transit time. Gain is further diminished by parasitic injection of carriers from the emitter that do not travel to the collector. Also, there is no accelerating field set up in the base by a dopant gradient such as occurs as a result of diffusion or implantation in the vertical structure. Some of these difficulties are partially solved using the FIB implantation and processing sequence we de-

scribe here. In particular we have used FIB implantation to produce well controlled, narrow ( $\sim 0.7 \mu\text{m}$  as-implanted) basewidth devices.

## II. PROCESS DESCRIPTION

Figure 1 is a schematic description of the process flow and resulting lateral bipolar transistor structure. The devices are made on *n*-epi islands, isolated by 1  $\mu\text{m}$  of field oxide, with  $N_D = 1.5 \times 10^{16}/\text{cm}^3$ . This becomes the nominal base doping that is later modified by FIB implants. The emitter electrode (and collector since the devices are symmetric) is pedestal-like, being fabricated on 100 nm of pedestal oxide. Contact to the  $p^+$ -doped polysilicon emitter electrode is via a 0.25  $\mu\text{m}$  polysilicon sidewall spacer which also acts as the source for doping the emitter active region via diffusion of dopants from the electrode. This method of combining pedestal isolation and diffusive formation of the emitter helps decrease parasitic effects. The polysilicon electrodes control the emitter to collector space ( $S$ ) which is defined by the master mask to be 3.0  $\mu\text{m}$ . This is decreased by the width of the sidewall spacer, diffusion during annealing, and the zero bias depletion width to produce an actual basewidth ( $W_B$ ) of about 1.7  $\mu\text{m}$  according to calculations with the Pisces two-dimensional device simulator. For the completed devices, the emitter and collector dimension perpendicular to current flow, was 10  $\mu\text{m}$ .

Two different experiments were run using FIB implants. In one case, a FIB boron implant ( $B^+$  at 75 kV,  $1 \times 10^{13}/\text{cm}^2$ ) extended the collector region to produce FIB-defined values for  $S$  of 0.5, 0.75, 1.0, 1.25, and 1.5  $\mu\text{m}$ . These widths were the result of utilizing the computer-aided design (CAD) mask data that defined the relative positions of the endpoints of the 3.0  $\mu\text{m}$  spacing and the FIB alignment marks, and using the FIB pattern generator that directed the beam to the proper position for the implants once beam alignment was accomplished. Taking into account the diffusion of boron from emitter and collector, and the sidewall spacer, Pisces simulations predict that a FIB-defined  $S$  of 1.25  $\mu\text{m}$  should result in an effective  $W_B$  near 0.2  $\mu\text{m}$ . In the

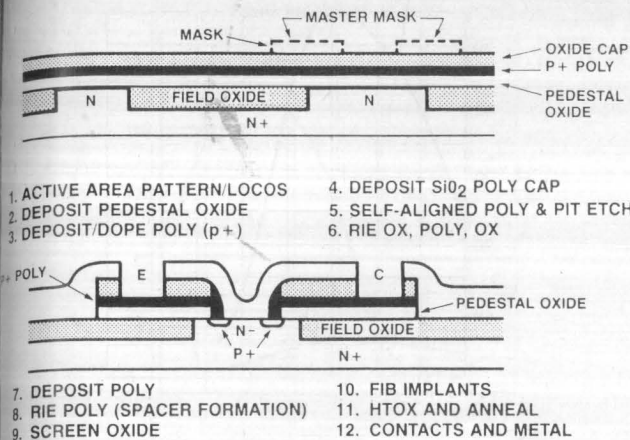


Fig. 1. Process flow and structure schematic for FIB-implanted lateral pnp bipolar transistor.

second experiment, two phosphorus implants into the base active region ( $P^+$  and  $P^{++}$  at 75 kV each with a dose of  $\times 10^{13}/\text{cm}^2$ ) were provided in the unimplanted space defined by the collector-extending boron implant used in the first experiment. As a limit these two implants could be used to define the  $W_B$  to be essentially the FIB diameter, i.e.,  $< 0.2 \mu\text{m}$  depending on the ion focusing column performance. We found that the  $P^{++}$  implants were necessary to prevent collector-emitter leakage due to carrier transport below the FIB  $P^+$  implant.

The focused ion beam implants were produced with a three-lens, mass-separating, variable-energy ion focusing column<sup>3</sup> with a beam having a full width at half-maximum intensity (FWHM) of  $\sim 0.2 \mu\text{m}$  for a quasi-Gaussian current density profile. Beam placement within the 150 by 150  $\mu\text{m}$  scanfield was estimated to have an accuracy better than  $0.45 \mu\text{m}$ . Implants of the active areas were achieved by scanning the FIB repeatedly over the desired region, with a beam overlap of 80% per scan, with the number of passes chosen to provide the proper dose. A single-liquid-metal alloy ion source using PdAsBP alloy on a tungsten needle and platinum heater ribbon reservoir<sup>4</sup> provided all the desired dopant ions for the experiment.

## EXPERIMENTAL RESULTS

Some devices on each wafer were not FIB-implanted. The performance of these comprised the base line for the experiment, i.e., these devices had the mask-defined  $S = 3 \mu\text{m}$  (leading to an effective  $W_B$  of  $1.7 \mu\text{m}$  according to Pisces simulation) and a base dose equal to that of the background epilayer ( $1.5 \times 10^{16}/\text{cm}^3$ ). For these base line devices, the values of  $h_{FE}$  (dc common emitter current gain) ranged from 6 to 10. In contrast, results for devices using the two different FIB-implantation protocols were obtained as follows.

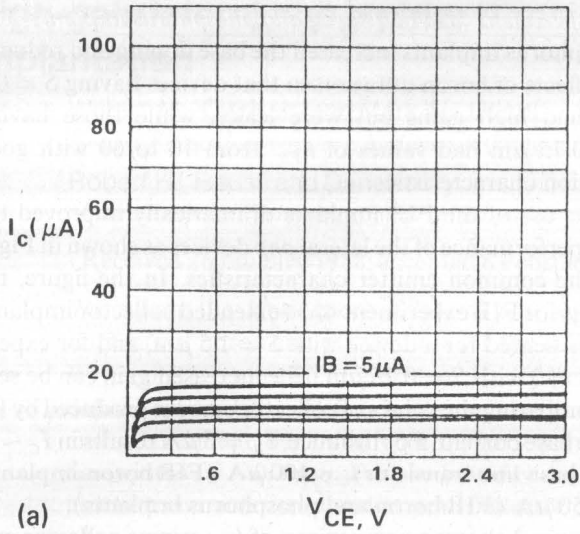
**Experiment #1: FIB boron (collector extending) implant only:** Devices with  $S < 1.25 \mu\text{m}$  were short circuited; those with  $S = 1.25 \mu\text{m}$  were marginally functional with values of  $h_{FE}$  from 100 to 300, but usually with excessive collector-emitter leakage. At  $S = 1.5 \mu\text{m}$ , the junctions exhibited low leakage and followed ideal diode behavior and the transistor values of  $h_{FE}$  varied from 40 to 100.

**Experiment #2: FIB boron and phosphorus implants:** The phosphorus implants increased the base doping and reduced the effects of boron diffusion so that devices having  $S = 0.5 \mu\text{m}$  had high gains but were leaky, while those having  $S = 0.75 \mu\text{m}$  had values of  $h_{FE}$  from 10 to 60 with good junction characteristics.

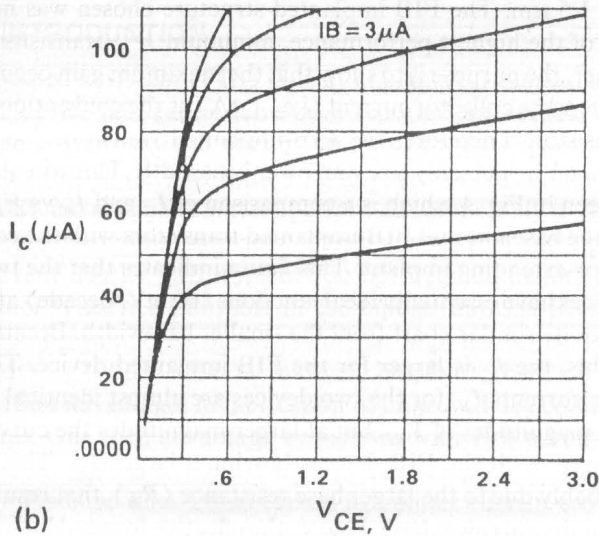
The use of the FIB implants dramatically improved the gain performance of the lateral pnp devices as shown in Fig. 2 via the common emitter characteristics. In the figure, the results for FIB experiment #1 (extended collector implant) are presented for a device with  $S = 1.5 \mu\text{m}$ , and for experiment #2 with  $S = 0.75 \mu\text{m}$ . The increased gain can be seen by comparing the values of collector current produced by the same base current. For instance,  $I_B = 3 \mu\text{A}$  results in  $I_C \sim 10 \mu\text{A}$  (base line transistor),  $> 100 \mu\text{A}$  (FIB boron implant), and  $50 \mu\text{A}$  (FIB boron and phosphorus implants).

Figure 3 shows a comparison of  $h_{FE}$  versus collector current ( $I_C$ ) for the base line transistor and a device receiving only the FIB collector-extending boron implant that defined  $S = 1.5 \mu\text{m}$ . The FIB implanted structure chosen was not one of the highest performance, minimum  $W_B$  transistors; rather, the purpose is to show that the maximum gain occurs at the same collector current (i.e.,  $1 \mu\text{A}$ ) as the conventional transistor. Therefore, the FIB-implanted transistor has a higher  $h_{FE}$  due only to a narrower basewidth. This can also be seen in Fig. 4 which is a comparison of  $I_C$  and  $I_B$  vs  $V_{BE}$  for the base line and FIB-implanted transistors with the collector-extending implant. This figure indicates that the two devices have essentially ideal junctions (60 mV/decade) and are quite similar apart from the smaller basewidth. Because of this, the  $I_C$  is larger for the FIB implanted device. The base currents  $I_B$  for the two devices are almost identical at low magnitudes of  $V_{BE}$  but at larger magnitudes the curves diverge, with the FIB device showing a larger  $I_B$ . This is probably due to the larger base resistance ( $R_B$ ) that results from the narrower base. Hence, the effective forward bias on the E-B junction is less, and there will be more parasitic injection into the substrate that will show up as increased base current. The potential for even higher gain devices is shown in Fig. 5, for which the FIB-defined  $S$  was  $1.25 \mu\text{m}$ . This figure indicates a peak  $h_{FE}$  of 175 at  $I_C = 0.1 \mu\text{A}$ , and a useful value of  $h_{FE} \sim 50$  at  $I_C \sim 60 \mu\text{A}$ .

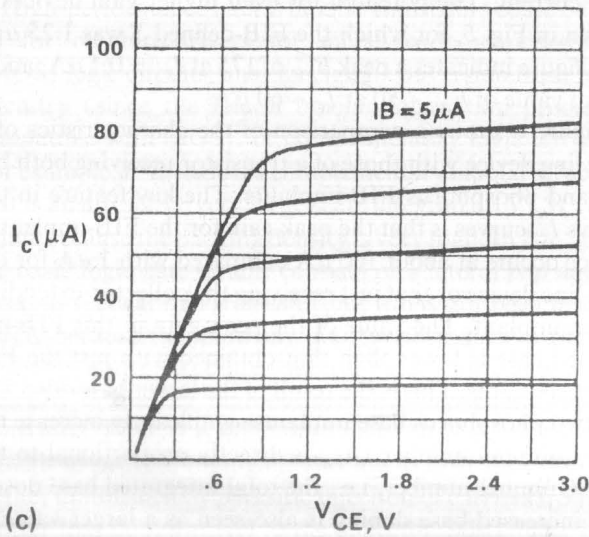
Figure 6 shows a comparison of the characteristics of a base line device with those of a transistor receiving both boron and phosphorus FIB implants. The key feature in the  $h_{FE}$  vs  $I_C$  curves is that the peak gain for the FIB-implanted device occurs at about  $100 \mu\text{A}$  compared with  $1 \mu\text{A}$  for the base line device or that just receiving the collector-extending boron implant. The value of the peak gain in this FIB-implanted case is lower than that obtained with just the FIB boron implants. This is the result of the larger base dose, i.e., the two phosphorus base implants significantly increase the base Gummel number ( $h_{FE}$  is directly proportional to the base Gummel number, i.e., the total integrated base dose). The increased base doping is also seen as a larger value of  $V_{CE0}$ , the collector-emitter breakdown voltage, ( $\sim 18$  vs  $12$  V). The slope of the  $I_C$  and  $I_B$  vs  $V_{BE}$  characteristics is 60 mV/decade for both devices indicating that the junctions have low leakage with ideal diode behavior.



(a)



(b)



(c)

FIG. 2. Common emitter characteristics for base line and FIB-implanted lateral pnp bipolar transistors. (a) Standard lateral pnp. (b) Lateral pnp with FIB-extended collector. (c) Lateral pnp with FIB-implanted base and collector.

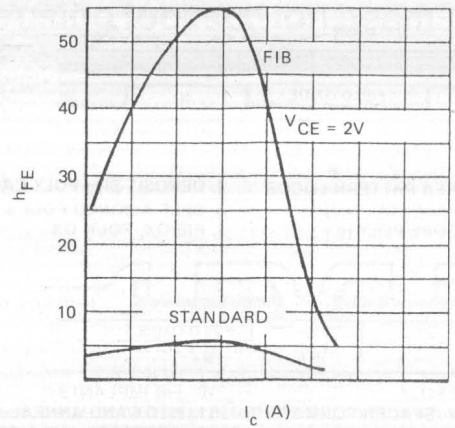


FIG. 3.  $h_{FE}$  vs  $I_c$  for base line and a FIB-implant collector-extending device with emitter-collector implant spacing  $S = 1.5 \mu\text{m}$ .

IV. DISCUSSION AND CONCLUSIONS

Using FIB implants of boron and phosphorus, we have fabricated pnp lateral bipolar transistors that have large gain due to the production of basewidths of  $0.2 \mu\text{m}$  or smaller in good agreement with simulation. Devices having good junction characteristics were made that had  $h_{FE}$  of 100, more than a factor of 10 larger than the base line devices. Devices with narrower basewidths had high-collector-emitter leakage but gains of 200–300. Use of the double phosphorus implants in the base were found to raise the collector-emitter breakdown voltage and increase the collector current ( $100 \mu\text{A}$ ) at maximum gain (by a factor of 100) compared to the base line device because of reduced  $R_B$ . In this case, the collector current at maximum  $h_{FE}$  is  $\sim 10 \mu\text{A}/\mu\text{m}$  of device width, and should be scalable to produce larger current devices for driver and digital-to-analog converter applications. That these multiple FIB-implanted devices have a maximum  $h_{FE}$  at larger currents due to lower  $R_B$  is the most important advantage of this technique. It is expected that the maximum gain can be increased by optimization of the base implant dose while maintaining low values of both  $R_B$  and collector-base capacitance. The results obtained should be considered

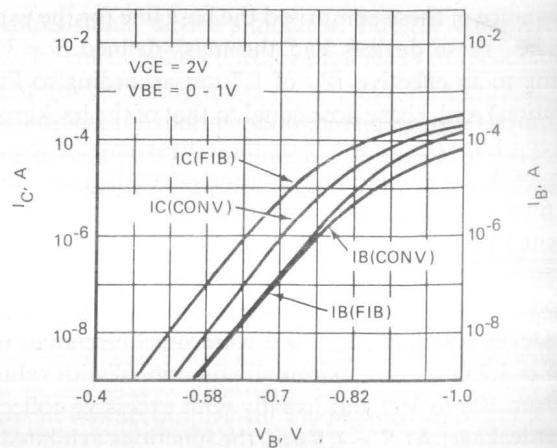


FIG. 4. Gummel plots for base line and FIB-implanted devices compared in Fig. 3.  $S = 1.5 \mu\text{m}$ .

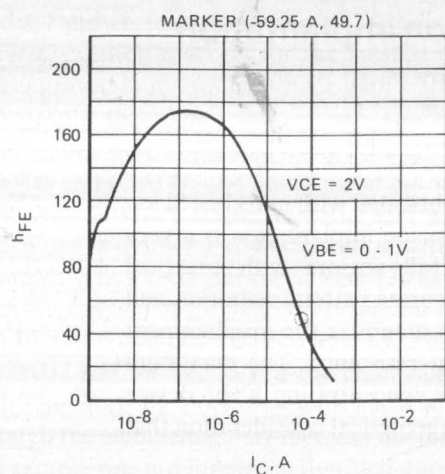


FIG. 5.  $h_{FE}$  vs  $I_C$  for FIB-implanted device with  $S = 1.25 \mu\text{m}$ .

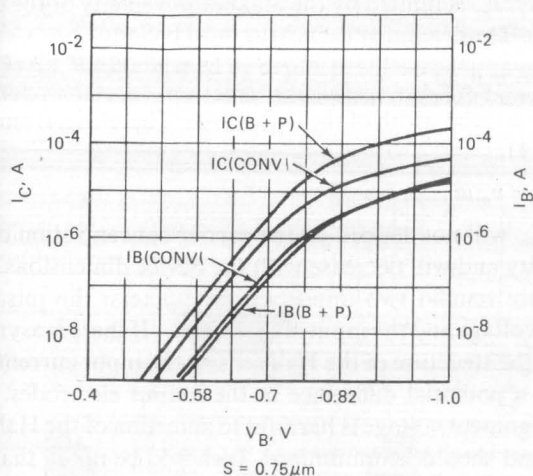
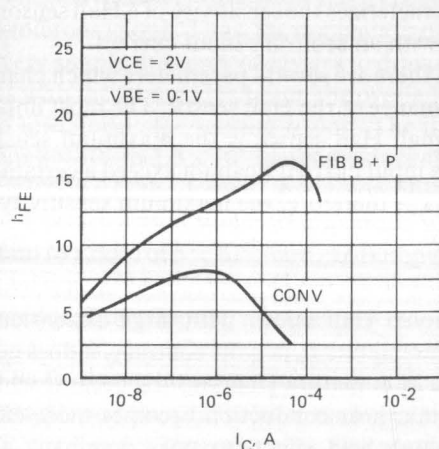


FIG. 6.  $h_{FE}$  vs  $I_C$  for base line and B and P FIB-implanted lateral bipolar transistor.

preliminary, since no attempt to optimize implant parameters was made, and show promise that FIB implants could fabricate lateral bipolar devices with characteristics predictable from simulations and which are useful in a number of applications.

Apart from use of the FIB implants, these lateral bipolar structures, the process flow, and the dc performance are comparable to those reported by Nakazato<sup>5</sup> for devices that operated at 3 GHz. In the case here, the use of the FIB permits greater flexibility in the device design. Specifically, the application of FIB to control  $W_B$  removes the uncertainty due to boron diffusion to determine basewidth and relaxes the requirement for stringent control of the anneal/diffusion cycle to achieve high performance.<sup>6,7</sup> The data show dramatically that the effect of decreasing the basewidth is to obtain larger values of  $h_{FE}$ . Use of both collector extending and base implants probably offers the best opportunity for high-performance devices since values of the doses, energy, and basewidth can all be adjusted for optimization.

Several extensions of this work can be envisioned. First of all, implantation of *npn* devices, and use of low-diffusion anneals would better utilize the advantages of FIB. This is because there would be less diffusion of carriers to decrease basewidth and add to processing uncertainty. Profiling the collector implant dose, from a large value at the collector contact to a lighter dose at the base junction (preferably less than the base dopant dose) could decrease collector resistance and better define and fix the position of the collector-base junction. Finally, the active base could also be profiled to provide an aiding field.

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