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Citation: Pilot Scholars Version (Modified MLA Style)

Reuss, Robert H.; Morgan, Damon; Goldenetz, Ann; Clark, William M.; Rensch, David B.; and Utlaut, Mark, "Fabrication of bipolar transistors by maskless ion implantation" (1986). *Physics Faculty Publications and Presentations*. 31.
http://pilotscholars.up.edu/phy_facpubs/31

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Fabrication of bipolar transistors by maskless ion implantation

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(Received 10 June 1985; accepted 13 September 1985)

The first focused ion beam (FIB) arsenic ion implants are reported. A shallow junction, vertical *npn* bipolar transistor fabricated by maskless implantation of B and As is described. For comparison, devices on the same wafer were also processed with conventional, broad-beam B and/or As implants. Good transistor performance is obtained for each type of implanted transistor. Device characteristics for FIB and conventional implants are generally the same. However, initial results indicate that diode quality and junction leakage appear somewhat degraded (excess generation–recombination) for FIB arsenic implanted devices. Characteristics of FIB boron implanted devices obtained over an extended period have been measured. These data indicate that wafer-to-wafer dose uniformity and quality (diode ideality and leakage currents) is equal to that for conventional implants (standard deviations $<10\%$). Device-to-device quality on a single wafer is also equal for the two techniques, while the device reproducibility is somewhat less for FIB, indicating some minor fluctuations in beam current (dose).

I. INTRODUCTION

The interest in and development of focused ion beam (FIB) implantation has increased significantly over the last few years.[1–3] Exploratory results have been published for silicon transistors[4–6] and resistors[7] fabricated with maskless FIB implants. Several groups have also reported FIB implanted GaAs devices.[8–10]

A major driving force for the interest in FIB is the reduction in the number of process steps and therefore the potential for improved yield and turnaround time.[2,3] The improvement in device performance which is theoretically possible with graded lateral dopant profiles[4] or $<0.5\ \mu$m implanted regions[6] is another major factor encouraging the development of FIB technology.

Before FIB implantation can have significant impact, however, further work in a number of areas is required. Key issues include availability of dopant ion sources and adequate characterization of the FIB implant process. Desired sources for the fabrication of GaAs devices have been demonstrated.[11] However, sources compatible with Si device fabrication have been more difficult to achieve.[12] With regard to understanding the implant process, differences in FIB and conventional, broad-beam implantation have been noted relative to lateral spread,[13] lattice damage,[14,15] and depth penetration.[16] That such differences in the two techniques can occur in some cases is not surprising, since the FIB current density ($\sim$A/cm^2) is 10^3–10^6 times higher. However, for device fabrication it is obviously necessary to be aware of the extent of the possible differences in implant characteristics. An equally important factor in the application of FIB implantation is the uniformity and reproducibility of the implant process. To date, no data relative to this question have appeared.

This paper reports progress in several areas relevant to the development of FIB maskless implantation. Specifically, the first totally FIB implanted (B and As) bipolar transistors are described. In addition, a further study[4] of FIB boron implanted transistors has been conducted to investigate the reproducibility of the FIB process. The device results for both FIB B and As implantation are shown to be comparable to those for conventionally (broad-beam) implanted transistors. The successful demonstration of an As ion source for device fabrication and good quality, reproducible transistors from the B source are encouraging results in the development of an FIB maskless silicon device fabrication capability.

II. EXPERIMENTAL

The process flow was similar to that previously described[4] and is summarized in Fig. 1. Starting wafers were ⟨100⟩ orientation, Sb doped ($\rho<0.01\ \Omega$ cm) with 1.8 μm As doped ($\rho=0.5\ \Omega$ cm) deposited epi. After the FIB implantation, selected regions of the wafer were conventionally implanted by means of positive photoresist masks. Implant damage was annealed and the dopants activated with one 1000 °C, 15 min anneal in N_2. Contacts and metal (Al/Si alloy) flows were accomplished by standard procedures. A

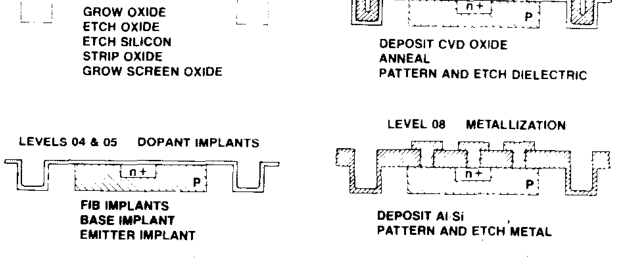

FIG. 1. FIB bipolar process flow.

schematic view (cross-sectional and plan) of the bipolar transistor is presented in Fig. 2. Four-point probe sheet resistance (R_s) patterns were also fabricated with the same mask set.

The FIB system[17] and implant procedures[4] have been previously described. The pattern was written by repeatedly scanning (depending on the desired dose) the beam having a pixel dwell time of 200 ns with an 80% overlap to insure uniform coverage. With the highest resolution ($1/e$ Gaussian spot $\sim 0.15\ \mu$m) beam defining aperture the B^+ target current is about 10 pA. Under similar conditions, the As^+ target current is over 25 pA. Higher target currents can be obtained by use of a larger beam defining aperture. The maximum source angular current intensities at a source extraction current of $20\ \mu$A are approximately $1.5\ \mu$A/sr for B and 9 μA/sr for As. These currents allow the base pattern ($80 \times 90\ \mu m^2$) to be written in 15 s and the emitter pattern ($20 \times 40\ \mu m^2$) to be written in 60 s.

All device data were recorded on an HP4145A semiconductor parameter analyzer controlled by an HP9836 computer. The ideality factors (*ID*) were measured from the slopes of the Gummel plots.[18] An average value of *ID* between 0.5 and 0.7 V was determined. The base resistance (R_B) was also extracted from Gummel plot data using the equation

$$R_B = \frac{\Delta V_{BE}}{\Delta I_B} - \frac{kT}{q \cdot \Delta I_B} \ln\left(\frac{I_{B2}}{I_{B1}}\right).$$

For convenience, R_b was calculated at 0.8 V. Incremental values of V near 0.8 V and the corresponding I_B were used.

III. RESULTS

A. FIB arsenic implanted transistors

Any adverse effects of FIB implantation should be easily detected by a shallow junction, bipolar transistor. As a minority carrier device, current gain (*Hfe*) is very sensitive to junction integrity. Shallow junctions ($\sim 0.25\ \mu$m for the emitter base and $\sim 0.50\ \mu$m for the base collector) are readily influenced by such factors as residual implant damage, enhanced dopant channeling or diffusion, and coimplanted or knocked-on impurities (metals, oxygen, carbon). Therefore, to assess the quality of the FIB arsenic implant, a series of transistors were fabricated on the same wafer. Four different versions were processed based on the process flow shown in Fig. 1. In the first case, both B (base) and As (emitter) were implanted with FIB. The remaining options consisted of an FIB emitter (As) and conventional B base, a conventional As emitter and FIB base, or all conventional implants.

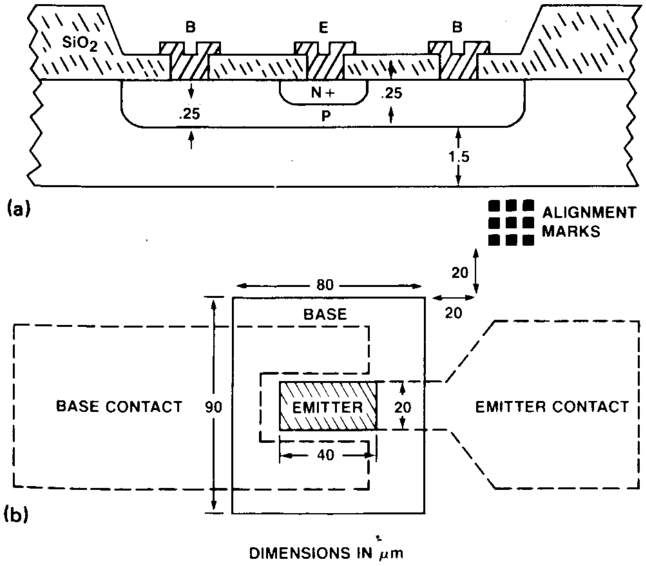

FIG. 2. Bipolar transistor structure: (a) cross-sectional view; (b) plan view.

The device characteristics for the FIB As implanted transistors from two wafers are summarized in Table I. As can be seen, good characteristics are obtained. Measured values are comparable to those expected based on results from devices with conventional implants. Note that for a constant base doping density, the *Hfe* increases with heavier arsenic doping because of the higher emitter Gummel number. In addition to demonstrating the viability of both As and B for FIB device fabrication, Table I also highlights the ease with which implant matrix parametric experiments can be conveniently and efficiently conducted. As shown in the table both base and emitter dose (as well as energy) can be varied on the same wafer.

While Table I shows that the *I–V* characteristics are consistent with expectations, in the long term the quality of the device is the major issue. In this regard, the Gummel plots[18] ($\log I_C$ and $\log I_B$ vs V_{BE}) shown in Fig. 3 are important. These are typical results from the same wafer for the four different implant options. Note that the characteristics are almost identical, particularly in the low current regime. The ideality factor (*ID*) for I_C in the region of V_{BE} from 0.40 to 0.70 V is approximately 1 for all the devices. The corresponding ideality factor for I_B is about 1.1 for the devices with a conventional arsenic implant while the FIB arsenic implanted devices show somewhat less ideal behavior ($ID = 1.3$).

Further indication of the quality of the FIB implanted devices from two wafers is seen in Table II. Diode ideality and emitter–base leakage should be sensitive indicators of contamination or residual implant damage. As shown in Table II (as well as Table III below), FIB implanted B results are equivalent to those for broad-beam implantation. However, there is a difference in performance for the FIB implanted As structures. The averaged diode leakage current (~ 140 pA) and the ideality factor for I_B (~ 1.3) are both higher than those with conventional As (~ 70 pA and ~ 1.07, respectively). This increase is indicative of excess generation–recombination centers. Although these are only preliminary efforts, the fact that good *I–V* characteristics are obtained for both FIB boron and conventional As suggests that the FIB arsenic may lead to device degradation. At present there is no explanation for the difference, but further work in this area is under way.

The general conclusion to be drawn from these measurements is that there is no drastic degradation in device performance attributed to the FIB process. Good results have been demonstrated with B. While some problems with As have been encountered, relatively little work has been performed with this ion source. Additional work is required to deter-

TABLE I. Device characteristics of FIB arsenic implanted transistors.

As emitter Dose ($\times 10^{15}$)	B base Dose ($\times 10^{13}$)	*Hfe*	V_{CBO}	V_{EBO}
2.5	1.0 (Conv.)	116	29.3	10.2
	0.8 (FIB)	147	30.7	13.5
5.0	1.0 (Conv)	134	29.0	10.1
	1.6 (FIB)	64	26.5	8.1
10.0	1.0 (Conv)	141	29.3	10.2
	3.0 (FIB)	37	26.0	6.5

mine if the differences detected are inherent in the process or just initial experimental difficulties.

B. FIB boron implanted devices

In earlier work,[4] FIB boron implantation was shown to provide device characteristics comparable to those from conventional implantation. A more detailed study of device quality and reproducibility is now reported.

Excellent reproducibility of device characteristics for a series of wafers processed at different times has been obtained. At least ten transistors at each dose are sampled to determine the average for the wafer. As shown in Table III, repeatability for the FIB implants is equal to that for the conventional. The standard deviation for the emitter base breakdown voltage is $< 5\%$ of the measured value for both implant techniques while the resistance measurements (R_b and R_s) have a standard deviation of under 10% (the larger variation is probably due to probe contact resistance rather than the implant process). Even *Hfe*, which can be easily varied by a variety of factors, shows comparable reproduc-

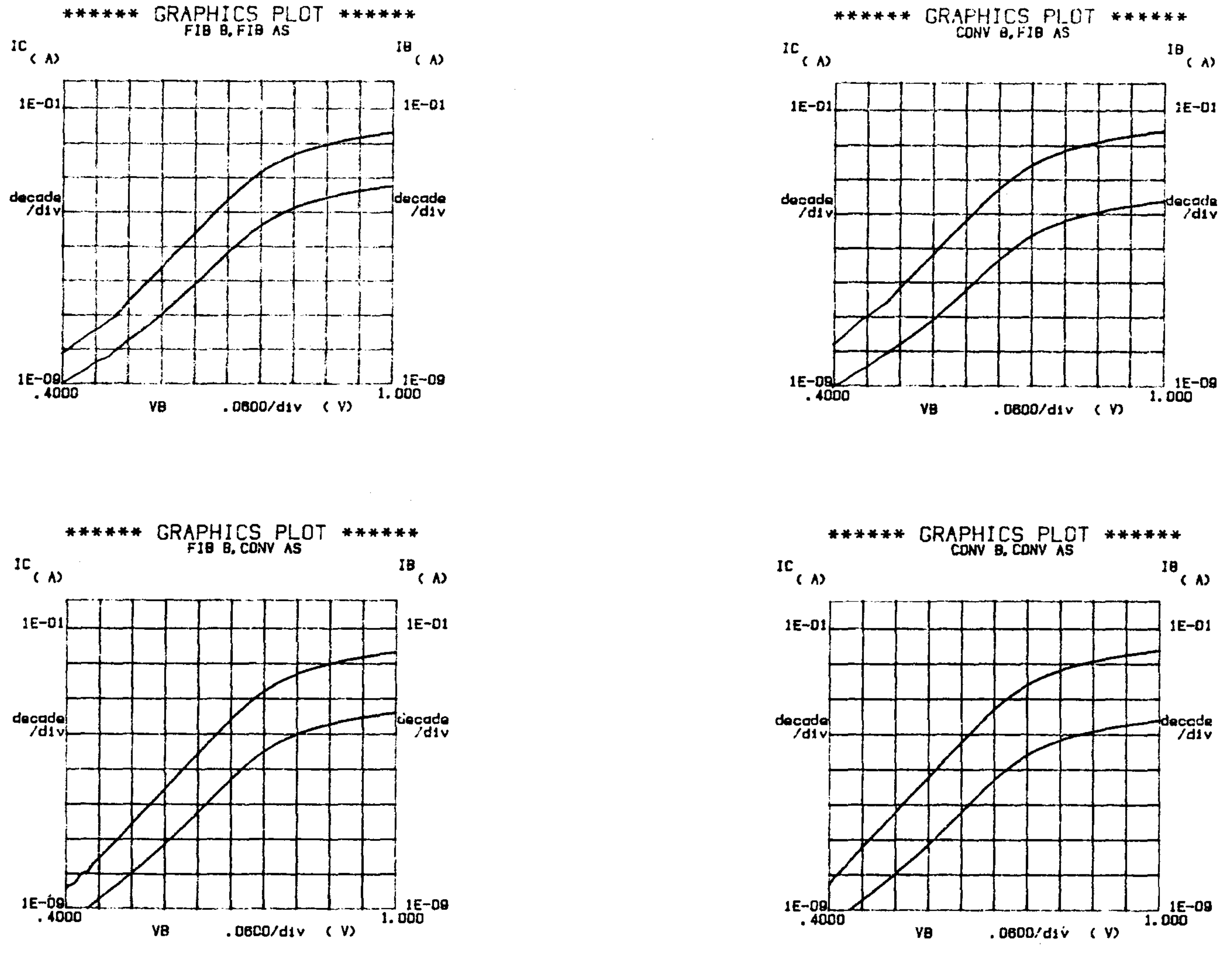

FIG. 3. Gummel plots for bipolar transistors: (a) FIB As and B; (b) FIB As and conventional B; (c) conventional As and FIB B; (d) conventional As and B.

TABLE II. Comparison of FIB vs conventional implantation of bipolar transistors.

As emitter	B base	No. of devices	*ID* (I_C) (std. dev., %)	*ID* (I_B) (std. dev., %)	I_R (*EB*0), pA (std. dev., %)
FIB	FIB	10	1.08(7)	1.30(15)	189(76)
		7	1.02(2)	1.06(3)	81(109)
FIB	Conv.	10	1.07(3)	1.56(25)	137(41)
		16	1.05(1)	1.21(8)	170(44)
Conv.	FIB	15	1.02(2)	1.07(3)	78(50)
		15	1.01(1)	1.04(2)	54(50)
Conv.	Conv.	15	1.03(0)	1.09(0)	103(25)
		15	1.00(1)	1.06(3)	36(139)

TABLE III. Wafer-to-wafer reproducibility of bipolar transistor characteristics: FIB vs conventional B implantation.

	B Dose ($\times 10^{13}$)	No. of wafers	*Hfe* (*pk*) (std. dev., %)	*EB*0 (V) (std. dev., %)	R_b (Ω) (std. dev., %)	R_s (kΩ/sq) (std. dev., %)
FIB	0.8	3	105(10)	9.6(3)	972(2)	3.2(7)
	1.6	5	49(10)	7.6(5)	511(12)	1.8(5)
Conv.	1.0	5	92(9)	8.9(2)	617(8)	2.8(9)
	1.5/1.6	7	53(20)	7.6(3)	458(10)	1.8(9)

TABLE IV. Device-to-device uniformity (footnote a). FIB boron vs conventional.

	Hfe(*pk*)	*ID*(I_C)	*ID*(I_B)	V_{CB0} (I_R)nA	V_{EB0} (I_R)pA	V_{CE0} (I_R)nA	R_B(kΩ) at 0.8 V
Conventional (B dose = 2×10^{13})	+ 32	+ 1.03	+ 1.14	+ 31.5(0)	− 7.2; 621	+ 21.7(0)	+ 0.358
	+ 32	+ 1.04	+ 1.12	+ 29.5(191)	− 6.9; 892	+ 13.2(289)	+ 0.362
	+ 32	+ 1.03	+ 1.12	+ 31.4(0)	− 6.7; 483	+ 16.7(1)	+ 0.361
	+ 33	+ 1.03	+ 1.12	+ 31.5(− 0)	− 7.1; 600	+ 22.1(− 0)	+ 0.369
	+ 32	+ 1.03	+ 1.13	+ 31.4(0)	− 7.3;1266	+ 21.2(0)	+ 0.364
	+ 32	+ 1.03	+ 1.11	+ 31.6(0)	− 7.2; 620	+ 19.5(0)	+ 0.344
	+ 32	+ 1.03	+ 1.11	+ 31.5(0)	− 7.2;1041	+ 19.5(0)	+ 0.345
	+ 32	+ 1.04	+ 1.14	+ 31.5(1)	− 7.2;1039	+ 19.3(0)	+ 0.345
	+ 32	+ 1.04	+ 1.11	+ 31.5(0)	− 7.2; 793	+ 21.2(0)	+ 0.343
	+ 32	+ 1.04	+ 1.12	+ 31.6(10)	− 7.2; 758	+ 14.4(1)	+ 0.356
Average	32.27	1.04	1.1	31.05	− 7.13(800)	19.2	348
Std. dev.	0.78	0.01	0.01	1.31	0.19(252)	3.07	11.8
(%)	2.4	0.5	1.3	4.2	2.6 (31)	15.8	3.4
FIB (B dose = 1.6×10^{13})	+ 46	+ 1.03	+ 1.08	+ 30.2(34)	− 8.0; 825	+ 12.5(35)	+ 0.439
	+ 47	+ 1.03	+ 1.07	+ 31.6(0)	− 8.1; 83	+ 15.4(0)	+ 0.440
	+ 49	+ 1.03	+ 1.06	+ 23.9(57)	− 8.1; 568	+ 12.2(805)	+ 0.450
	+ 49	+ 1.03	+ 1.07	+ 31.7(0)	− 8.0; 59	+ 16.3(0)	+ 0.443
	+ 51	+ 1.03	+ 1.07	+ 31.8(0)	− 8.3; 68	+ 14.8(0)	+ 0.460
	+ 45	+ 1.03	+ 1.08	+ 31.7(0)	− 6.9; 83	+ 14.4(0)	+ 0.424
	+ 45	+ 1.03	+ 1.07	+ 31.6(0)	− 8.0; 103	+ 15.8(0)	+ 0.419
	+ 45	+ 1.03	+ 1.07	+ 31.7(0)	− 7.6; 159	+ 18.1(0)	+ 0.423
	+ 45	+ 1.03	+ 1.07	+ 31.7(2)	− 7.9; 127	+ 13.4(0)	+ 0.426
	+ 61	+ 1.11	+ 1.00	+ 23.8(999)	− 8.0; 622	+ 11.2(865)	+ 0.421
Average	52.54	1.04	1.08	30.97	− 8.14(150)	14.83	464
Std. dev.	10.85	0.01	0.02	2.42	0.60(183)	1.68	69.8
(%)	20.6	0.9	1.9	7.8	7.3 (122)	11.3	15.0

[a] 26 devices each.

ibility for the two implants [the 20% standard deviation for the broad-beam case is due to the combination of results for doses of (1.5) and $(1.6)\times 10^{13}/\text{cm}^2$]. While more extensive data are desirable, the results obtained to date indicate that the variation introduced by the FIB boron implant process is no greater than that inherent in the fabrication and measurement processes.

In addition to reproducibility, the other major concern in device fabrication is the quality of the junction. The data shown in Table IV (for both ideality and emitter base diode leakage) demonstrate that on the same wafer FIB implanted transistors of quality equal to that for conventional implants are reproducibly achieved. The fact that $ID(I_C)$ and $ID(I_B)$ are very close to the ideal value of 1.00 indicates that few excess generation–recombination sites have been created (and no more than that due to conventional implantation). Diode leakage is also comparable for the two techniques. (The higher value of I_R shown in Table IV is typical for p^+n^+ diodes, and is not considered significant. Lower values of about 100 pA are observed for conventional implants at lower dose.)

The on-wafer, device-to-device reproducibility data summarized in Table IV (for 26 devices of each type) indicate that FIB transistors do have a somewhat larger variation in *Hfe*, emitter base breakdown voltage, and base resistance (R_B). These parameters are dose related and demonstrate that small variations in ion source current occur. While some current drift over time is apparent, no evidence of significant nonuniformity within an implant region has been observed. Rather, thermal wave dose measurements have demonstrated that uniformity across an implant region fluctuates no more than a few percent.[19] The somewhat larger variation in device-to-device characteristics for FIB as compared to conventional B implants is not considered to be serious at this stage of development. Increased uniformity is expected as the ion sources are improved.[20]

The ideality and leakage data indicate that defect density and impurity levels (metals, knock-on) for FIB boron implantation are no different than those for conventional implantation. Similar results have been obtained on other wafers. Based on the available data, as summarized in Tables II–IV, it appears that with the exception of a small device-to-device variation, there is no difference between conventional and FIB boron implantation under the conditions used in these experiments.

IV. SUMMARY

Significant progress towards the development of an FIB implant process for Si device fabrication has been demonstrated. An As ion source for FIB implantation has been demonstrated to provide devices comparable to those for broad-beam implants. Functional bipolar transistors have been fabricated with both implants performed by FIB. The results indicate that no serious degradation in device characteristics is caused by FIB. However, there does appear to be a small increase in generation–recombination centers.

A number of wafers with both FIB and conventional B implanted devices were processed. The data indicate that the quality and reproducibility of the two are equal. Wafer-to-wafer standard deviations of only a few percent are obtained. The device-to-device dose uniformity for FIB devices show that small fluctuations in ion current do occur with time.

ACKNOWLEDGMENTS

The assistance of Motorola SRDL wafer processing personnel is gratefully acknowledged. Thanks are also due Donna Blakely for typing the manuscript.

[1] A. Wagner, Solid State Technol. **26**, 97 (1983).
[2] G. Dunn and E. M. Kellogg, Semicond. Intl. **7**, 139 (1984).
[3] M. Hassel Shearer and G. Cogswell, Semicond. Intl. **7**, 145 (1984).
[4] R. H. Reuss, D. Morgan, E. W. Greeneich, W. M. Clark, Jr., and D. B. Rensch, J. Vac. Sci. Technol. B **3**, 62 (1985).
[5] R. L. Kubena, J. Y. Lee, R. A. Jullens, R. G. Brault, P. L. Middleton, and E. H. Stevens, IEEE Trans. Electron Devices **ED-31**, 1186 (1984).
[6] S. Shukuri, Y. Wada, H. Masuda, T. Ishitani, and M. Tamura, Jpn. J. Appl. Phys. **23**, L543 (1984).
[7] H. Hamadeh, J. C. Corelli, A. J. Steckl, and I. L. Berry, J. Vac. Sci. Technol, B **3**, 91 (1985).
[8] E. Miyauchi and H. Hashimoto, Nucl. Instrum. Methods B **7/8**, 851 (1985).
[9] T. Shiokawa, P. H. Kim, K. Toyoda, S. Namba, T. Matsui, and K. Gamo, J. Vac. Sci. Technol. B **1**, 1117 (1983).
[10] R. L. Kubena, C. L. Anderson, R. L. Seliger, R. A. Jullens, E. H. Stevens, and I. Lagnado, J. Vac. Sci. Technol. **19**, 916 (1981).
[11] H. Arimoto, A. Takamori, E. Miyauchi, and H. Hashimoto, J. Vac. Sci. Technol. B **3**, 54 (1985).
[12] T. Ishitani, K. Umemura, S. Hosoki, S. Takayama, and H. Tamura, J. Vac. Sci. Technol. A **2**, 1365 (1984).
[13] E. Miyauchi, H. Arimoto, Y. Bamba, A. Takamori, H. Hashimoto, and T. Utsumi, Jpn. J. Appl. Phys. **22**, L423 (1983).
[14] M. Tamura, S. Shukuri, T. Ishitani, M. Ichikawa, and T. Doi, Jpn. J. Appl. Phys. **23**, L417 (1984).
[15] Y. Bamba, E. Miyauchi, H. Arimoto, A. Takamori, and H. Hashimoto, Jpn. J. Appl. Phys. **23**, L515 (1984).
[16] Y. Bamba, E. Miyauchi, M. Nakajima, H. Arimoto, A. Takamori, and H. Hashimoto, Jpn. J. Appl. Phys. **24**, L6 (1985).
[17] V. Wang, J. W. Ward, and R. L. Seliger, J. Vac. Sci. Technol. **19**, 1158 (1981).
[18] S. M. Sze, *Physics of Semiconductor Devices*, 2nd ed. (Wiley, New York, 1981), pp. 134–140.
[19] R. H. Reuss, W. L. Smith, W. M. Clark, and D. B. Rensch, in *Proceedings of the 1985 Materials Research Society* (in press).
[20] W. M. Clark and M. Utlaut (to be published).