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Edited by A G Cullis and D B Holt

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TEM investigation of the effect of anneal temperature and arsenic concentration on the polysilicon/thin oxide/single-crystal-silicon emitter of a new high-performance bipolar transistor

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Abstract A new type of Si bipolar transistor is being fabricated by a conventional ion-implantation process but with the emitter consisting of a polysilicon/thin-oxide-film/single-crystal Si combination. TEM lattice-image and weak-beam examinations were performed to investigate the effect of different annealing temperatures and different dopant concentrations. The observed structures are correlated with the measured transistor gains.

1. Introduction

Bipolar transistors are being fabricated so that higher gains and/or operating frequencies can be obtained without having to reduce device dimensions. The fabrication is based on standard ion implantation processes except that the emitter consists of a combination of polysilicon, thin oxide film and single-crystal silicon (Fig.1). The presence of the oxide film modifies the flow of electrons and holes through the device so that the base current is reduced. For the device to be successful, the oxide film ideally needs to be continuous, uniform and of the correct thickness, both when initially formed and at the end of the fabrication process. Initial oxide film thicknesses in the range ~0.5 to ~2.5nm are being investigated.

The standard fabrication procedure used for such devices is as follows. (100) n-type Si slices are B⁺ ion implanted to form the base. The slices are given a chemical solution 'cleaning' treatment to produce the thin oxide film. A polysilicon layer is deposited, and the layer is As⁺ ion implanted and given an oxidation drive-in. The drive-in causes the As to diffuse rapidly down the grain boundaries of the polysilicon, through the oxide film and into the underlying single-crystal Si to form the e/b junction.

Previous TEM examinations of such structures (Wilson et al 1982, Albu-Yaron et al 1984) using an As⁺ ion dose of $5 \times 10^{15} \text{ cm}^{-2}$ and a drive-in at 1000°C showed that the oxide became increasingly non-uniform and eventually 'balled-up'. As this occurred the underlying single-crystal silicon progressively 'penetrated' the oxide film and grew into the polysilicon layer, the latter eventually becoming entirely single-crystal. An

oxidation drive-in temperature of 1000°C is clearly too high for such device fabrication, and so for the continuation of the project the drive-in temperature was reduced to 900°C.

In the present work two separate experiments were performed, each based on a slightly different fabrication procedure (Table). Firstly, the Si slices were 'cleaned' using an RCA solution (HCl , H_2O , H_2O_2). After the polysilicon layer deposition, and before the As^+ ion implantation, the slices were pre-annealed at either 900, 950 or 1000°C. The aim of this experiment was to 'break-up' the oxide film by the pre-anneal, and then to see what effect this had on the subsequent device fabrication. Control specimens were prepared using an HF 'clean'. Secondly, the Si slices were 'cleaned' using an HF/SP solution (HF followed by H_2SO_4 , H_2O_2). The slices were implanted with As^+ ions to doses of either 5×10^{15} , 1×10^{16} or $2 \times 10^{16} \text{ cm}^{-2}$. The aim of this experiment was to see what effect different As concentrations had on the device fabrication procedure. Control specimens were prepared using an HF/SP/HF solution (HF followed by SP followed by HF).

TEM examinations were made of the various slices corresponding to the stage after the oxidation drive-in. Plan-view and cross-sectional specimens were prepared by mechanical polishing and Ar^+ ion-beam milling. Two-beam, weak-beam and (110) lattice-imaging examinations were performed using Philips EM300 and JEOL 200CX instruments. The observed structures were correlated with the measured transistor gains (Table).

2. Experiment 1

For the RCA/900°C specimen, the TEM lattice-image cross-section micrographs (Fig.2a) showed that the oxide film was slightly non-planar, but was nevertheless continuous and of uniform thickness $1.4 \pm 0.2 \text{ nm}$. For the RCA/950°C specimen, the oxide film was more irregular and in some regions the underlying single-crystal Si was just beginning to penetrate into the polysilicon (Fig.2b). For the RCA/1000°C specimen, many regions were now penetrated, the regrown areas extending up to $\sim 100 \text{ nm}$ into the layer (Fig.2c).

For the HF/no-pre-anneal specimen, an oxide film of thickness $0.8 \pm 0.2 \text{ nm}$ was present, but this was penetrated in many places, the regrown areas extending up to $\sim 2 \text{ nm}$ into the layer (Fig.3a). For the HF/1000°C specimen, the oxide film was extensively 'balled-up', large areas of the polysilicon layer being regrown (Fig.3b). The oxide 'balls' were up to $\sim 5 \text{ nm}$ across.

3. Experiment 2

For the HF/SP/no-implant specimen, the oxide film was planar and of uniform thickness $1.0 \pm 0.2 \text{ nm}$ (Fig.4a). For the HF/SP/ $5 \times 10^{15} \text{ cm}^{-2}$ specimen, the oxide film was slightly non-planar but was nevertheless still continuous (Fig.4b). For the HF/SP/ $1 \times 10^{16} \text{ cm}^{-2}$ specimen, the oxide film was penetrated in many places (Fig.4c). For the HF/SP/ $2 \times 10^{16} \text{ cm}^{-2}$ specimen, the penetration was greater with the regrown areas extending up to $\sim 35 \text{ nm}$ into the layer (Fig.4d).

For the HF/SP/HF/no-implant specimen, the oxide film was very thin and not continuous (Fig.5a). For the HF/SP/HF/ $5 \times 10^{15} \text{ cm}^{-2}$ specimen, the oxide film was balled-up and the regrown areas extended $\sim 50 \text{ nm}$ into the layer (Fig.5b). For the HF/SP/HF/ $1 \times 10^{16} \text{ cm}^{-2}$ specimen, and also the

HF/SP/HF/ 2×10^{16} cm $^{-2}$ specimen, the behaviour was similar except that all of the polysilicon layer had regrown (Fig.5c). The oxide 'balls' were up to ~ 4 nm across.

4. Discussion

The RCA, HF/SP and HF 'cleans' produced initial oxide films of thickness ~ 1.4 , ~ 1.0 and ~ 0.8 nm respectively, while the HF/SP/HF 'clean' produced an initial oxide film which was still thinner and possibly discontinuous in places.

For all of the specimens investigated, a consistent trend occurred. When the oxide film was continuous, the transistor gain was high (for the particular type of transistor). When the oxide film was initially penetrated, the gain decreased. When the oxide film 'balled-up', the gain further decreased. The 'break-up' of the oxide film was more rapid when the temperature was higher, and when the As concentration was higher.

The reason for the 'break-up' of the oxide film is considered to be due mainly to a reduction in energy due to a decrease in the total area of the oxide/silicon interfaces. Our previous analysis (Albu-Yaron et al 1984) indicated that this 'break-up' occurred without significant change taking place in the total volume of the oxide, i.e. the behaviour was associated with local diffusion. A possible reason why the increased As concentration increased the oxide film 'break-up' is that As segregated at the oxide film interface, and this As either increased the local diffusion rate or decreased the oxide/silicon interfacial energy.

Acknowledgments

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 Albu-Yaron A, Barry J C and Booker G R 1984 Proc. 8th European Congress on Electron Microscopy ed A Csanady (Budapest) p521

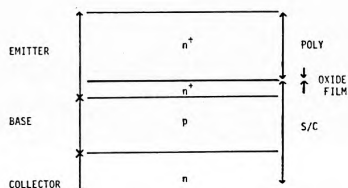


Fig.1 Schematic of a device structure.

Clean	Poly (nm)	Anneal (°C)	As ⁺ dose (cm ⁻²)	Drive-in (°C)	Gain
RCA	400	900	1×10^{16}	900	1300
RCA	400	950	1×10^{16}	900	360
RCA	400	1000	1×10^{16}	900	90
HF	400	-	1×10^{16}	900	250
HF	400	1000	1×10^{16}	900	50
HF/SP	200	-	0	-	-
HF/SP	200	-	5×10^{15}	900	22
HF/SP	200	-	1×10^{16}	900	12
HF/SP	200	-	2×10^{16}	900	5
HF/SP/HF	200	-	0	-	-
HF/SP/HF	200	-	5×10^{15}	900	2
HF/SP/HF	200	-	1×10^{16}	900	4
HF/SP/HF	<200	-	2×10^{16}	900	5

Preparation conditions and device gains.

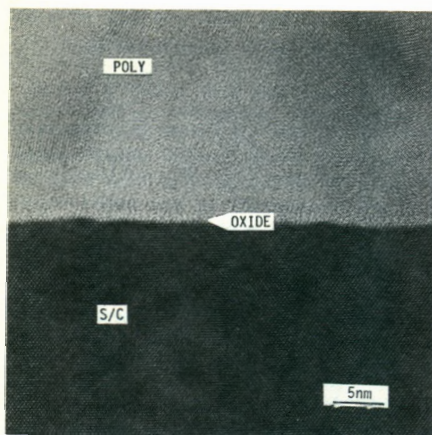


Fig.2a RCA cleaned slice pre-annealed at 900°C for 10 min.

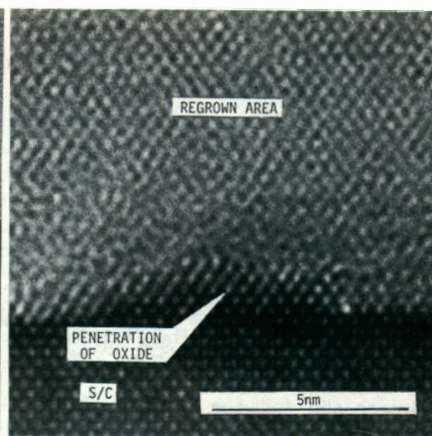


Fig.2b RCA cleaned slice pre-annealed at 950°C for 10 min. Note the epitaxial re-alignment of the poly-silicon layer.

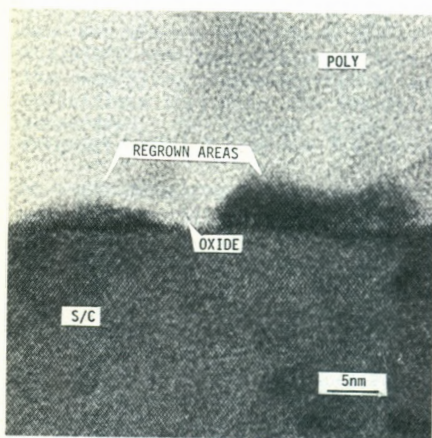


Fig.2c RCA cleaned slice pre-annealed at 1000°C for 10 min. Note the areas of epitaxial re-alignment and the oxide break up.

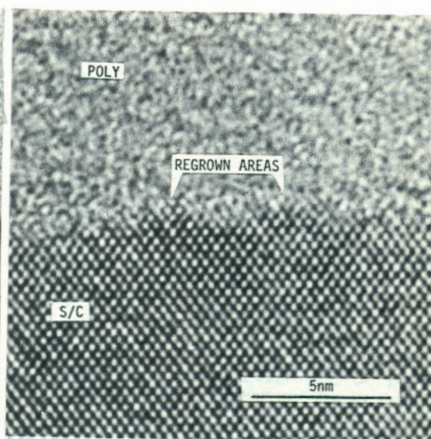


Fig.3a HF cleaned slice not pre-annealed. Note the small areas of epitaxial re-alignment.

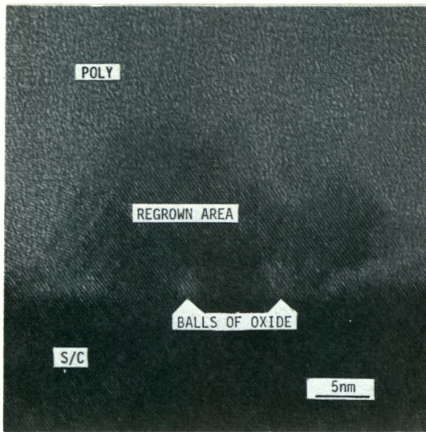


Fig.3b HF cleaned slice pre-annealed at 1000°C for 10 min. Note the large areas of epitaxial re-alignment, and the balled-up oxide.

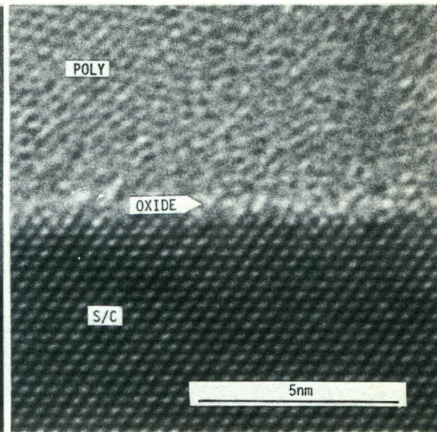


Fig.4a HF/SP cleaned slice which had not been implanted. Note the continuous oxide film.

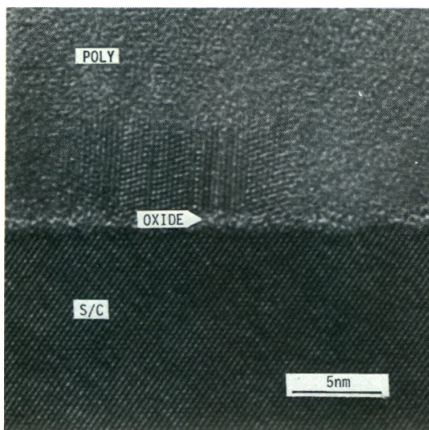


Fig.4b HF/SP cleaned slice after $5 \times 10^{15} \text{ cm}^{-2} \text{ As}^+$ and 900°C for 15 min. Note the uneven, but continuous oxide film.

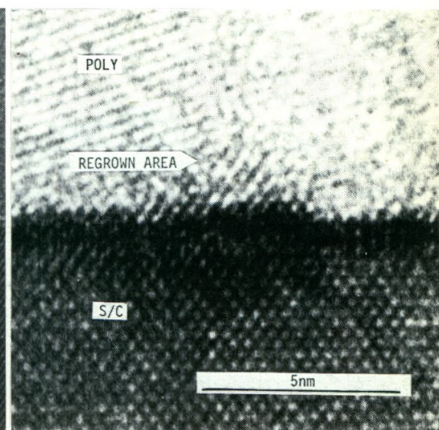


Fig.4c HF/SP cleaned slice after $1 \times 10^{16} \text{ cm}^{-2} \text{ As}^+$ and 900°C for 15 min. Note the small area of epitaxial re-alignment.

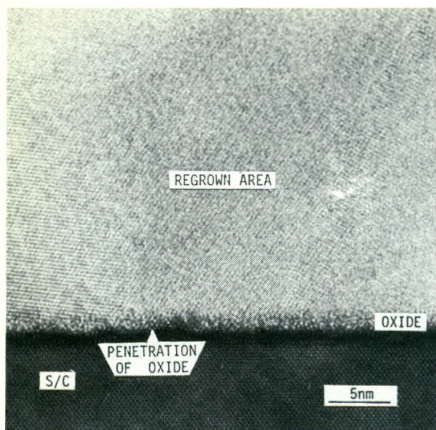


Fig.4d HF/SP cleaned slice after $2 \times 10^{16} \text{ cm}^{-2} \text{ As}^+$ and 900°C for 15 min. Note the large area of epitaxial re-alignment, and the point of penetration of the oxide film.

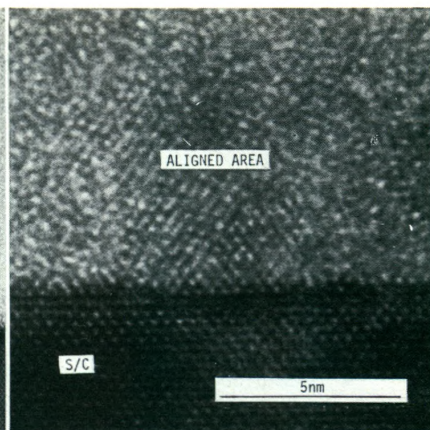


Fig.5a HF/SP/HF cleaned slice which had not been implanted. Note the aligned region in the polysilicon.

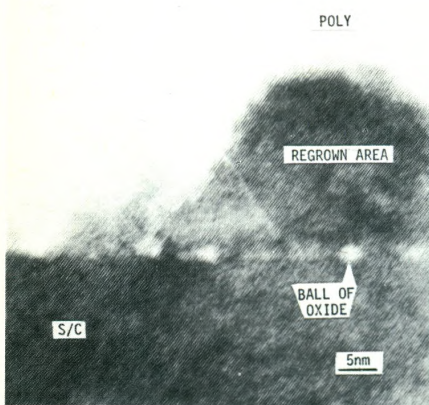


Fig.5b HF/SP/HF cleaned slice after $5 \times 10^{15} \text{ cm}^{-2} \text{ As}^+$ and 900°C for 15 min. Note the large epitaxially re-aligned area and the balling-up of the oxide film.

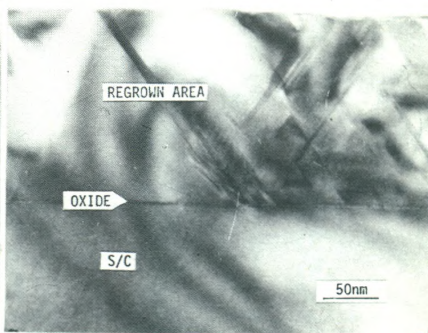


Fig.5c HF/SP/HF cleaned slice after $1 \times 10^{16} \text{ cm}^{-2} \text{ As}^+$ and 900°C for 15 min. The polysilicon layer has regrown completely.