Photolithography development for the IMS T800 floating-point transputer

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The large size of the IMS T800 coupled with its high pattern density and 1.25 μm minimum design rules place new constraints on volume VLSI production, particularly in the photolithography area of manufacture. In early 1986, the authors decided to take advantage of advances in lens and process technology to extend their lithographic capabilities at 1 μm resolution over a wide (22 mm) exposure field. This development is now virtually complete, with the unique and powerful T800 device running successfully in volume production. The technology decisions and the installation and evaluation results obtained using the new technology are described.

Keywords: *photolithography, semiconductor devices, transputer*

Photolithography is a key area in the manufacture of modern advanced semiconductor devices. As individual circuit features become diminished the control of three particular parameters becomes important:

- printed defects,
- printed feature size,
- layer-to-layer registration.

The T800, compared with the standard transputer, has an additional 16 kbit of onboard static memory, bringing the total to 32 kbit, and a 64 bit floating-point processor with associated microcode ROM. This makes the T800 a large die with a complex process involving small minimum feature size and a high number of masking layers. Each of these has implications for the implementation of a manufacturable lithographic process.

Each of the critical parameters is discussed in turn, and the technology choices behind them that result in the successful production of working devices on first silicon are described.

Printed defects

Inmos uses direct-step-on-wafer-reduction cameras (steppers) in its photolithographic area. The principle involved is that a mask (reticle) consisting of a small number of devices can be guaranteed defect-free and then can be stepped out over the whole area of a silicon wafer. Using an automatic optical image processor prior to stepping, the reticle is inspected for defects by comparing one die with an adjacent die. Any differences are highlighted as possible defects which can then be checked and the reticle cleaned or rejected as necessary.

The importance of reticle cleanliness is instantly apparent when one considers that a large number of Inmos products have only two die per reticle frame. A defect on just one reticle can instantly reduce yield by 50%. There are 14 photolithographic layers involved, and defects on any two reticles could reduce yield to zero.

The T800 introduces new considerations as its die size, 8.66 × 10.87 mm, is such that only one could fit on the reticle frame of a standard stepper with a datafield diagonal of 20 mm. This would then mean that the technique just described could not be used to check for defects. Clearly, a single defect would be catastrophic. This is made worse by the fact that the process enhancements used to increase the on-board memory also add three extra masking layers to the process.

In order to overcome the problems of defect inspection, three options were considered:

- a die-to-database inspection system,
- alternate frame glass-wafer inspection with a duplicate reticle set,
- a stepper lens with a field wide enough to accommodate two T800s.

Die-to-database inspection

After the design of a device on a CAD system, the data is fractured and put into a format compatible with electron beam mask-making equipment. The data tape sent to the mask makers essentially tells the electron beam when to switch on and off while scanning such that the correct pattern is generated

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on the reticle. This process can be done in reverse in order to inspect a reticle. If the reticle is optically scanned and the image digitized, then this can be compared with the original data tape and any differences highlighted as defects.

Two systems were on the market at the time of the start of this project. However, both were found to have inadequate database conversion software, complicated by the size of database involved. To put the database size into perspective, the T800 includes more than 250 000 transistors. The layer defining the metal-to-transistor connections has nearly 1 M contact holes. Each of these has to be correct.

Both systems were also very expensive (>\$1 M) and this option was therefore discounted.

Duplicate reticle set

Running a production line with a large number of different devices and with each device having a large number of reticles means that reticles are changed frequently. Once a reticle has been accepted from the maker, then it is when it is being changed that it is most likely to pick up a defect. In order to inspect a reticle once on a stepper, a technique known as glass-wafer inspection is used.

When the reticle is first put onto a stepper,a pattern is printed on a glass wafer onto which a thin film of titanium has been sputtered (50 nm). After titanium-etching and photostrip, this wafer can be inspected on the same image-processing equipment as a reticle and hence defects can be detected. The only problem with this technique, in general, is that the image inspected is a five times reduction of the reticle. (For example, 2 μm defect at the reticle will print at 0.4 μm, yet the sensitivity of the system is only 0.5 μm; a 0.4 μm defect could act as a potential bridging site and hence be critical.)

If one had two duplicate single-die reticle sets, then the reticles could be used alternately to print adjacent die on a single glass wafer. This, when inspected in the normal way, would indicate differences between the reticle sets. It would not, however, provide complete immunity, as the same defects could be on both reticle sets. The actual inspection procedure is also very complex for what has to be a routine production operation. These factors, plus the lower intrinsic detection sensitivity, meant that this option was not pursued.

Wide-field stepper lens

Two T800 devices plus necessary street structures on a reticle would have a datafield diagonal of 21.84 mm. A lens was available from the manufacturer of the Inmos steppers, GCA, as a retrofit that had a specified 22 mm diameter field. It would therefore be possible to have a two-die reticle and use the standard defect-inspection procedures if this lens met our other requirements.

The lens, a Tropel 2232G, has a numerical aperture of 0.32 and was designed to operate at the wavelength of the mercury G-line. This gives it a resolution specification in production of 1.0 μm, this resolution to be achievable over the full 22 mm field and through a 2.0 μm range of focus. The minimum feature to be printed for the T800 is 1.25 μm, and the lens specification therefore met the authors' immediate requirements – and gave scope for next-generation products. This aspect of the photolithography development will be dealt with in the following section.

The other lens specification was that of lens distortion. Inmos specifies that the lens-reduction error plus distortions over the full field should be less than 0.2 μm. This is a key specification, as it has implications on layer-to-layer registration between systems. The technology behind distortion measurements will be discussed later.

Printed feature size

The photolithographic process essentially involves exposing a photoactive compound (photoresist) with the required pattern and then selectively removing those parts that have been exposed (positive process). The remaining photoresist then acts as either an etch or an implant mask for the next processing step.

The fundamental property of the photoresist is then the image transfer from the aerial image, supplied by the stepper/lens, into a physical image. It is the dimensional control of this resultant physical image that is of paramount importance in producing a correctly functioning semiconductor device.

The T800 is currently produced in Newport on 100 mm diameter wafers and with a 22 mm diameter field size. The dimensional control required is such that there is a total range of linewidth of:

Across reticle frame = 0.15 μm
Across wafer = 0.15 μm

This translates to a dimensional specification of ±0.15 μm from the nominal (ie at cell poly definition, linewidth specification = 1.2–1.5 μm).

Assuming a constant photoresist process, the cross-frame uniformity is dictated by the quality of the lens, and the cross-wafer uniformity by the photoresist process. The large field size would tend to make the cross-frame control more difficult as vignetting alone causes a 2% exposure variation centre-edge of field. Different photoresists can enhance, or otherwise affect, the total linewidth control. The photoresist process is hence extremely critical in meeting the required specifications.

In a photoresist process, there are perhaps eight major parameters, each of which is dependent on the others, and a large amount of engineering is therefore required before a full process evaluation. This optimization work is not presented here, although the results as they relate to production are.

The following criteria were used:

- The resolution capability of the lens must be fully used, and perhaps enhanced.
- The processing conditions must have sufficient latitude to allow the dimension control requirements to be met in volume production.

Resolution

After optimization, the photoresist was exposed such that approximate 1 : 1 line : space ratio resulted. The wafer was then examined under a scanning electron microscope and micrographs taken showing the image of 1.0 μm and 0.8 μm sets of features at three different points on the field of the lens (see Fig 1).

The 1.0 μm features are resolved at all points on the lens, and the 0.8 μm features in the centre of the lens. These demonstrate the lens capabilities very clearly.

On acceptance, the lens resolution was measured at its extremes of field and focus, measuring orthogonal images, and it was found to achieve specification throughout. Fig 2 shows the micrographs, the measurements of which are summarized below. (All units are in microns.) These SEMs and the data confirm the lens resolution and

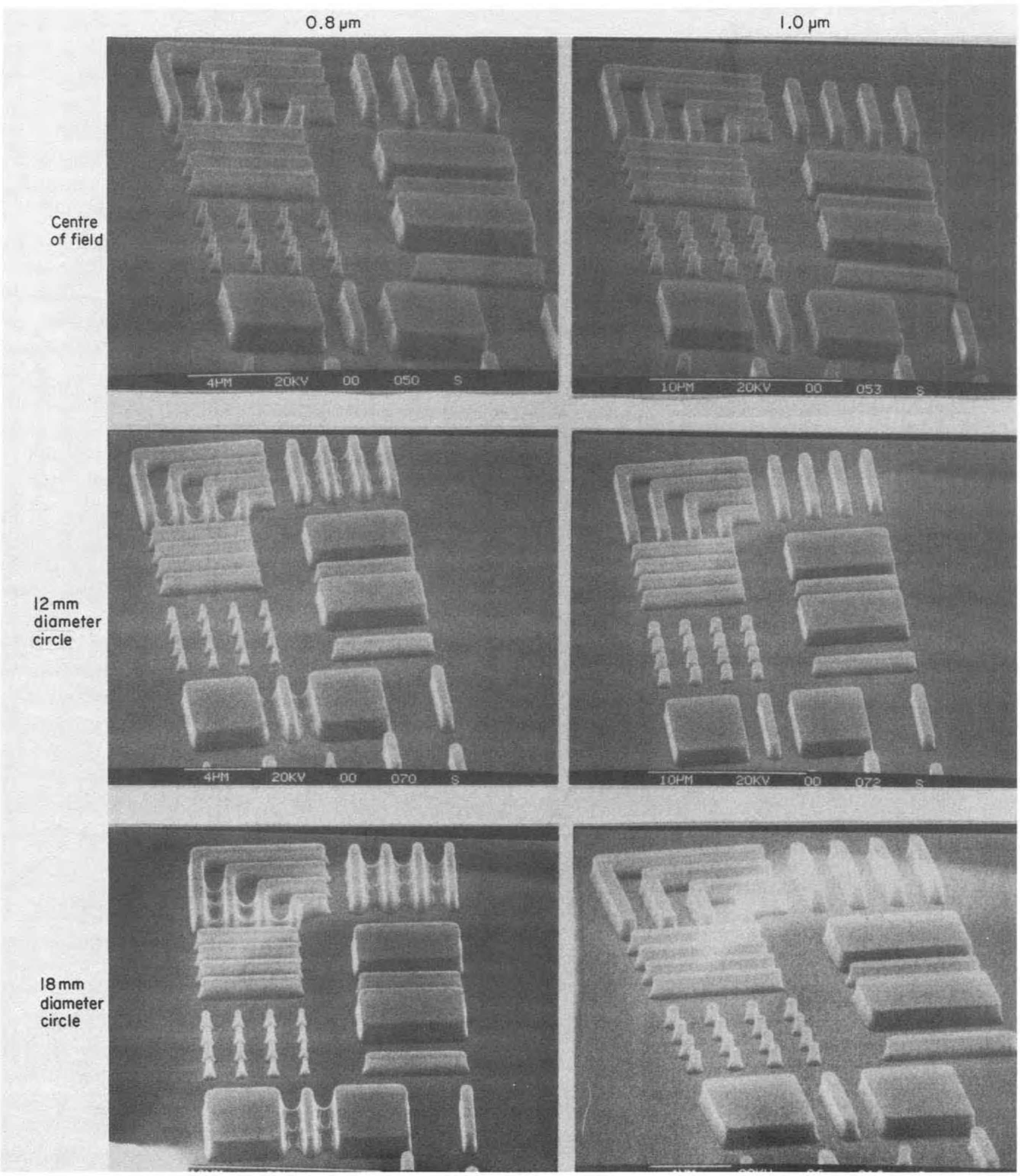

Fig 1 Cross-frame resolution, optimized photoresist process

Fig 2 Micrographs

Table 1 Measurements of micrographs shown in Fig 2

Focus	Mean	Standard deviation	Range
+1	1.01	0.04	0.15
Opt.	0.99	0.04	0.12
−1	1.00	0.04	0.15

focus specifications. (The measurements are on a 1.0 μm line.)

Looking again at Fig 1, the 0.8 μm features that are not resolving actually indicate the 'failure' mechanism. As the resist is exposed monochromatically (436 nm), and there is a fair degree of coherence (0.6) within the stepper optics, a 'standing wave' effect is seen. Reflections from the substrate add to the exposure energy delivered to the resist, and nodes of maximum and minimum exposure can be seen on the SEM photoresist sidewall. Looking at the 0.8 μm feature at 12 mm diameter, one can see the node of minimum exposure just not clearing out. This then implies that further resolution enhancements could possibly be made using an antireflective coating or some kind of contrast-enhancement layer. These have the disadvantage of increasing the required exposure dose by up to 100% and hence decreasing stepper throughput. This technology option was not pursued for the T800 process as the resolution just demonstrated is easily adequate.

Process Latitude

The two main process variables are exposure energy and stepper focus. To best measure the effect of these on linewidth, a wafer is exposed with a matrix of foci and exposure printed on it. Exposure can be increased across the wafer and focus down the wafer. The linewidth at each exposure site can then be measured and characteristic graphs plotted. Characteristic graphs for the process are shown in Fig 3.

The first graph shows the rate of change of linewidth with exposure at various foci, and the second graph the rate of change of linewidth at various exposures. These give useful information about the whole photolithographic process.

Looking at the gradient of linewidth versus exposure at optimum focus, one can see a very shallow curve (<0.15 μm per 100 mJ). The ±1 μm defocus curves follow this very closely and only begin to diverge by more than 0.1 μm at the highest exposure energy. The ±2 μm focus curves are more scattered, but even then, at the exposure that one would choose to use (155 mJ), the linewidth is almost identical. This graph also shows very clearly how the ±1 μm defocus specification relates to production.

The graph of linewidth versus focus essentially indicates the best operating exposure. At an exposure of 155 mJ, there is no real change of linewidth with focus. This is known as the

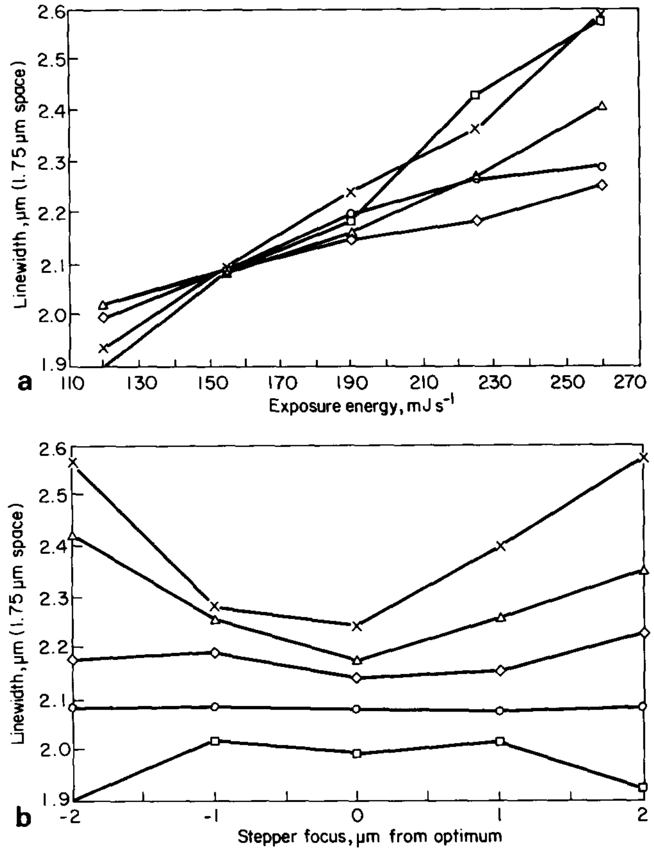

Fig 3 Process characteristic graphs; (a) Inmos T800 photolithography, linewidth against exposure, □ = −2 μm, ○ = −1 μm, ◇ = optimum, △ = +1 μm, x = +2 μm; (b) linewidth against focus, □ = 120 mJ, ○ = 155 mJ, ◇ = 190 mJ, △ = 225 mJ, x = 260 mJ

conjugate exposure' and is an extremely stable point to operate at. Stepper focus is very dependent on the refractive index of air (ie atmospheric conditions), and so it is desirable to bias the reticle by such an amount that one can run at the conjugate exposure. In this case, the exposure gives a linewidth approximately 0.3 μm different to that designed on the reticle and this is therefore the bias to use.

Summary

The wide-field lens fully meets the linewidth specifications, and, in conjunction with an optimized photoresist process, the processing latitude with respect to exposure and focus is extremely good. Putting this into production, in the manufacture of the first engineering samples of the T800, the cross-frame linewidth was within the 0.15 μm specification at every layer, and the 1.25 μm minimum features were printed with no difficulty.

Registration

There are a number of contributing factors to layer-to-layer misregistration:

- reticle writing errors (specification ⩽ ±0.15 μm),

- lens–lens matching errors (specification $\leqslant \pm 0.20\ \mu m$),
- autowafer align errors (specification $\leqslant \pm 0.35\ \mu m$),
- reticle placement accuracy (specification $\leqslant \pm 0.05\ \mu m$),
- stage precision (specification $\leqslant \pm 0.05\ \mu m$).

The total overlay budget allowed by the design rules is $\pm 0.5\ \mu m$ for each layer to the previous target layer. (Calculated by taking the RMS errors.)

Each of these is clearly very important, particularly with the large number of masking layers, and each is reviewed in turn.

The auto wafer align (AWA) system has the largest error margin, but this is a fundamental part of the stepper and there is little scope for additional creative engineering. This system essentially looks at targets on the left and right extremes of each wafer and then moves to the centre of a TV screen, thereby correcting for *X*, *Y* and theta. The system is sensitive to the contrast of the target, and so aligns some process layers better than others. It is also off-axis, meaning that the microscopes it uses to view the wafer can move relative to the optical axis of the system (during a temperature excursion, for example). This can result in extra error due to 'baseline drift'.

The recticle placement and stage-precision errors are both fairly small, but are measured frequently to ensure repeatable stepper performance. The stage errors become important in volume production when stage-to-stage precision is being considered. A technique to match stages is employed. This uses the same technology as that used to match lenses and is described below in some detail.

The reticle writing errors are largely in the hands of the vendors, although it is possible to measure the difference at the field edge between each reticle in a set and a master reticle. The technique used, once again, is related to that used to measure lens distortion.

The contribution to misregistration due to lens distortion is perhaps the most interesting for two reasons. First, in production, registration is measured using optical verniers which are placed typically in the centre of the reticle. This means that a lens distortion, which affects the edge of the field, will not be detected until poorly yielding product reaches probe. Second, to make parts in any volume requires the use of a number of steppers, each stepper lens having different errors.

A technique was required whereby the lens-distortion errors could be measured accurately and the correctable errors acted upon. Steppers that were matched to each other in terms of both lenses and stages could then be defined.

Standard lens-distortion measurements use optical verniers placed at eight sites on a reticle frame. These verniers are accurate to only about $\pm 0.05\ \mu m$. With the low number of sampling points and the required $\pm 0.2\ \mu m$ maximum error, these would be inadequate. A better system had to be devised for these measurements.

To resolve this at Inmos, a reticle was designed with structures that enabled electrical wafer probing to give precise misalignment data. Powerful in-house software routines were also developed such that the probe data could be easily manipulated to yield lens or stage errors.

Electrical registration measurement

Fig 4 shows the design of the electrical registration structure used. It is a modification of the standard Stickmann resistor, such that the same structure exposed twice with a small shift between exposures results in a set of alignment resistors in both *X* and *Y*. (A diagram of the overlayed structure is presented in Fig 5.) A Van der Pauw structure is also included with the 'unit cell' for local sheet resistivity measurements. The unit cell is placed 212 times on a reticle to cover that area of datafield used by a transputer (see Fig 6).

To understand how this reticle is used, consider

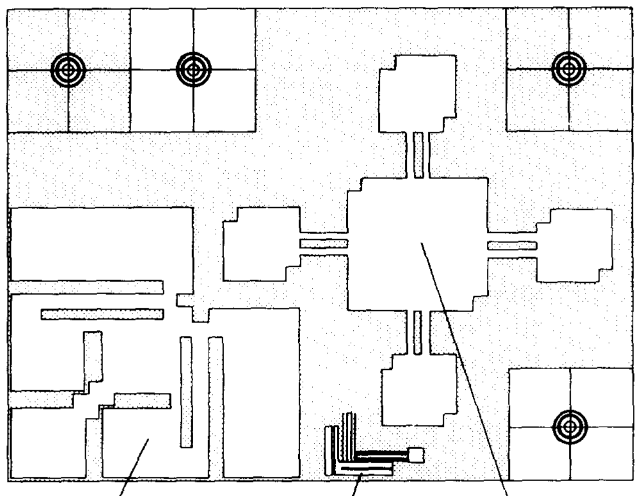

Fig 4 Unit cell electrical registration structure

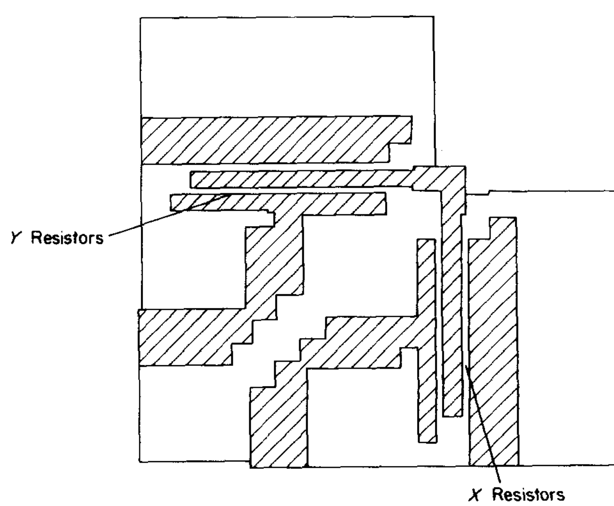

Fig 5 Overlayed registration structure. (The shaded areas are not a feature)

the process flow for a typical test:

1 Doped polysilicon substrate
2 Photoresist coat
3 Exposure 1, 2
4 Develop
5 Etch
6 Electrical probe
7 Software analysis

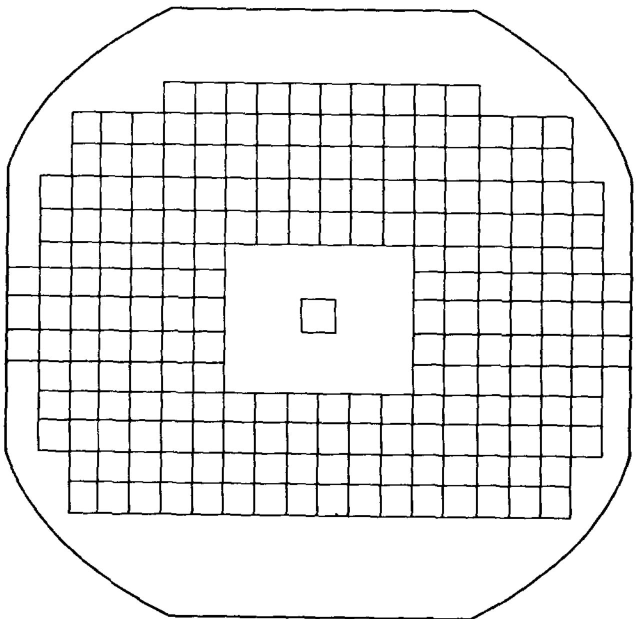

Fig 6 Reticle layout

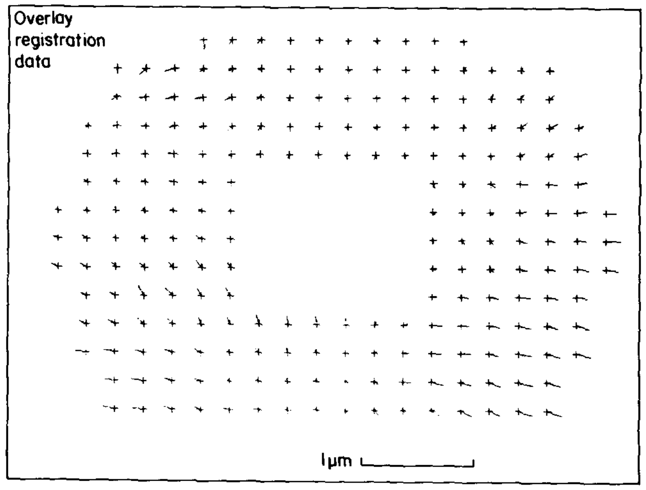

Fig 7 First lens-distortion map

Stepping jobs can be designed using this reticle specifically to look at lens distortion or stage matching/precision. Lens distortion is done using a two-pass exposure job. The first pass exposes the full field of the reticle, while the second pass steps out the central cell over each of the 212 first-pass cells. The stages are controlled by a laser interferometer which has a precision of one $\lambda/16$ laser count—0.04 μm. The lens is hence mapped to the stage grid, stage-precision errors being removed by repeating this five times on one wafer and averaging the data.

To measure stage errors between steppers, the central cell is exposed over the whole wafer on a master stepper and the image developed. The same wafer is then aligned on the test stepper and the same pattern exposed, with appropriate shift. This

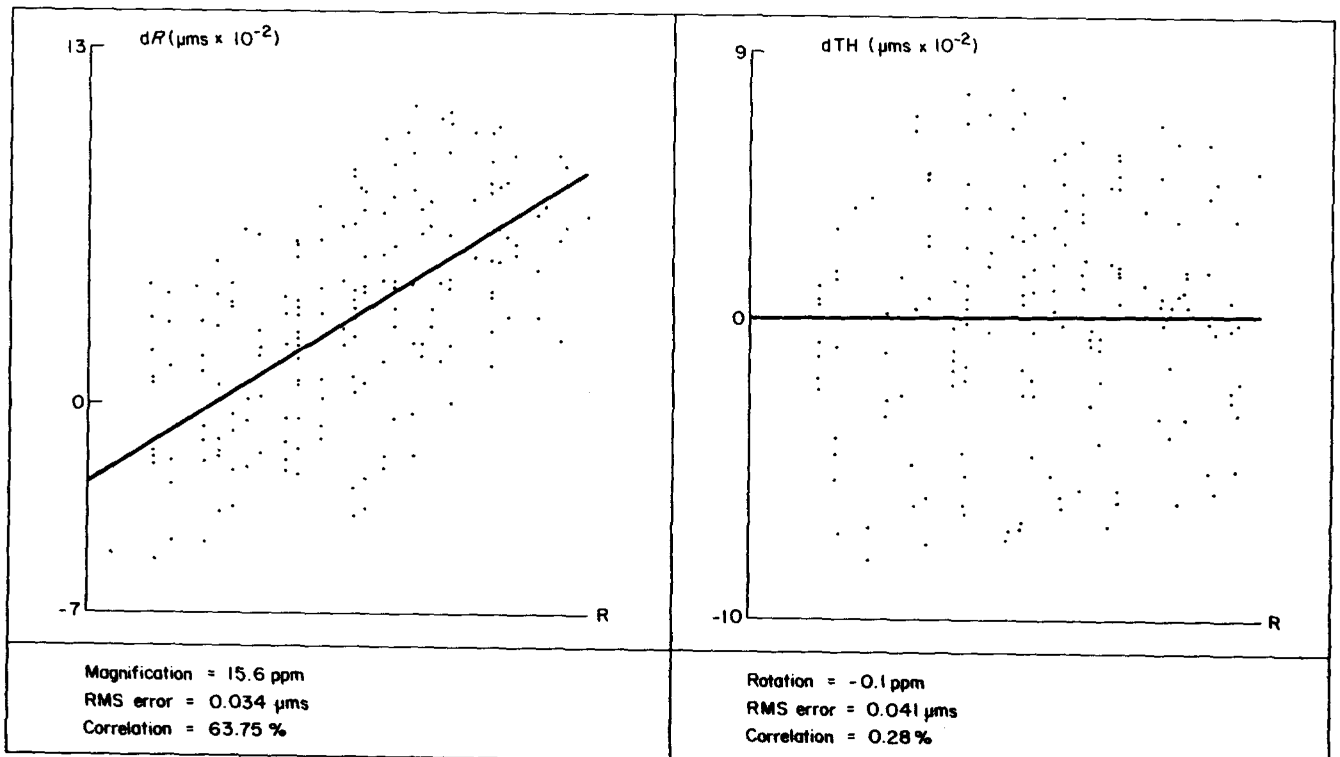

Fig 8 Polar errors showing rotation and reduction

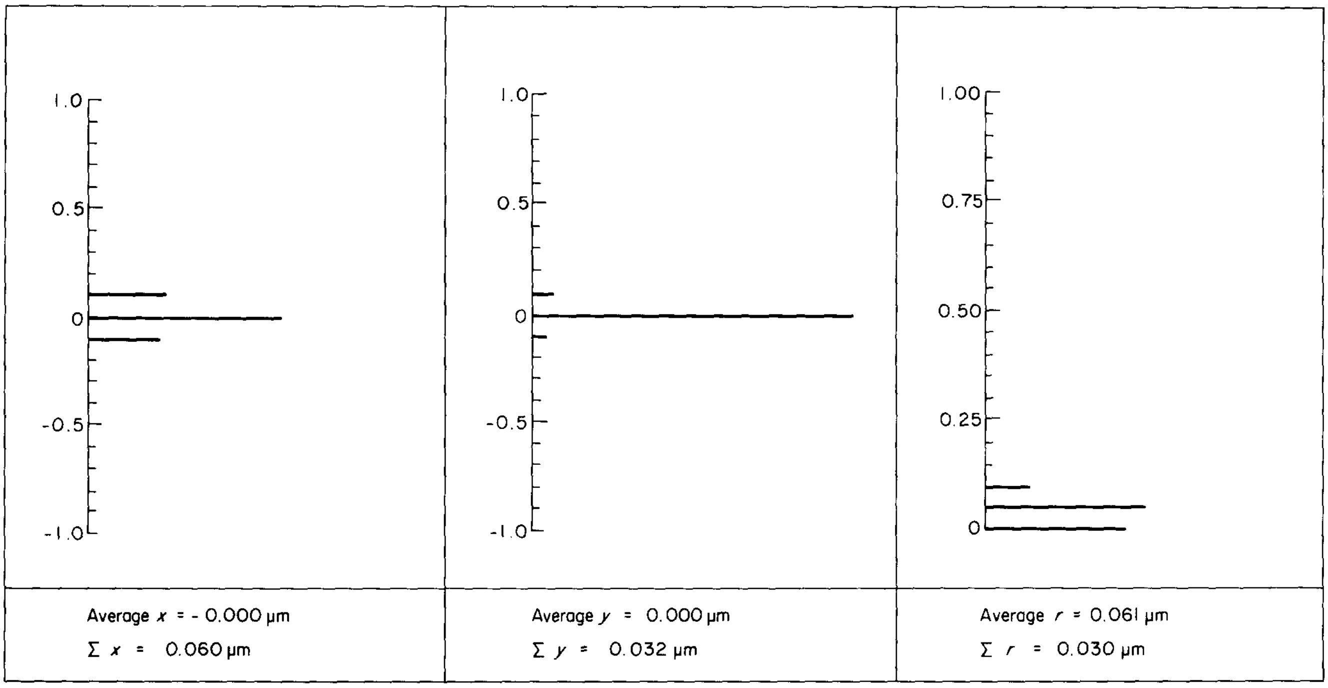

Fig 9 Working array statistics

then results in a relative measure between the stages.

The electrical probing of the wafers after etch is relatively simple. The two resistors that define X and the two that define Y are measured at each site along with the sheet resistivity. This data is then sent to a central computer where it can be transformed into misalignment in X and Y using a simple relationship:

$$\text{Misalignment} = 0.5\ pL(1/R_1 - 1/R_2)$$

where p is the sheet resistivity, L is the resistor length and R_1, R_2 are the resistances. This data can then be manipulated.

Results

Figs 7 to 9 show the lens distortion map of the first Tropel lens accepted with associated 'polar' errors

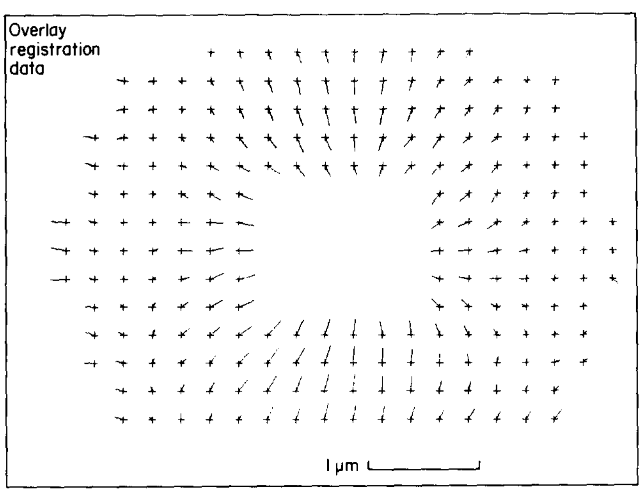

Fig 10 Second lens-distortion map

and statistics. The polar errors indicate that there is no reticle rotation yet there is a reduction error of 15 ppm. The statistics show the distribution of misalignments across the lens in terms of X, Y and the vector **R**. All points are within the 0.2 μm specification.

Figs 10 to 12 show the same results for the second lens accepted. This time, a large reduction error is indicated, though the intercept is not at zero. Looking in more detail at this lens, Fig 13 shows a representation of lens anamorphism, showing an error of up to 16 ppm. This is a non-correctable lens error, unlike reduction, and is an indication of the different design criteria used by Tropel, the manufacturer of the lens. No anamorphism is seen on the standard Zeiss lenses used on the Inmos steppers.

This anamorphism uses up nearly half the total allowed distortion error, but even so all points fall within the allowed specification.

Fig 14 shows the overlay of the two lenses on each other performed to a specification of 0.18 μm. This shows that the lenses are a matched pair, i.e. Inmos has the capability of volume T800 production.

The whole process from coat to data analysis typically takes 12 h in production, although it could take as little as 3 h if pushed. This means that this is a very real technique for measuring lens errors down to below 0.01 μm, and it has very real uses in matching steppers to provide maximum production capability.

Conclusions

The photolithographic processes involved in the manufacture of semiconductor devices have been reviewed and those issues that are impacted by the

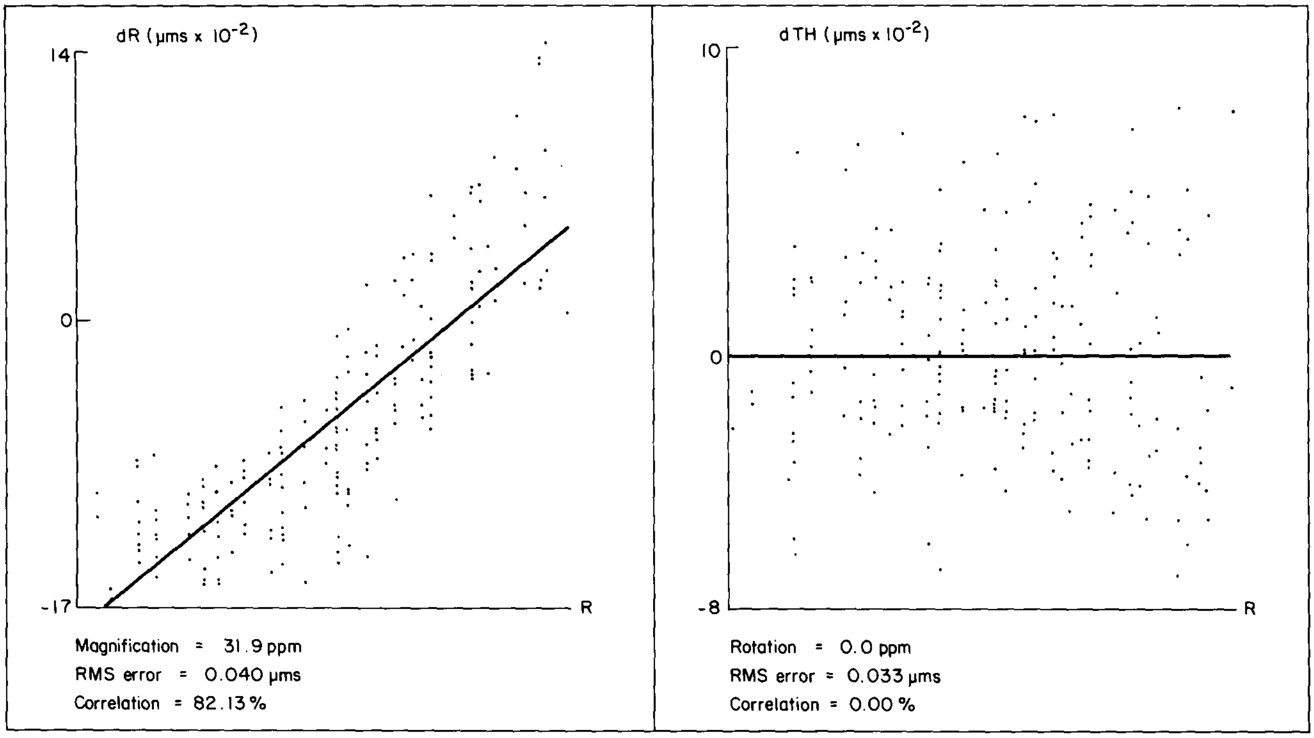

Fig 11 Polar errors showing rotation and reduction

large die size of the T800 have been highlighted. The difficulty of inspecting single-die reticles for defects was the factor determining the choice of a wide-field stepper lens. The act of choosing a lens resulted in a review of both the photoresist process and lens-distortion technology.

The lens/resist combination was shown to be able to print 1.0 μm resolution over the full field and through the depth of focus of the lens. From a production viewpoint, the process latitude was easily within controllable limits, and no problems were found meeting the required linewidth specifications. The micrographs shown also indicated possible areas of development to further enhance the capabilities of the lens.

The whole issue of alignment was discussed,

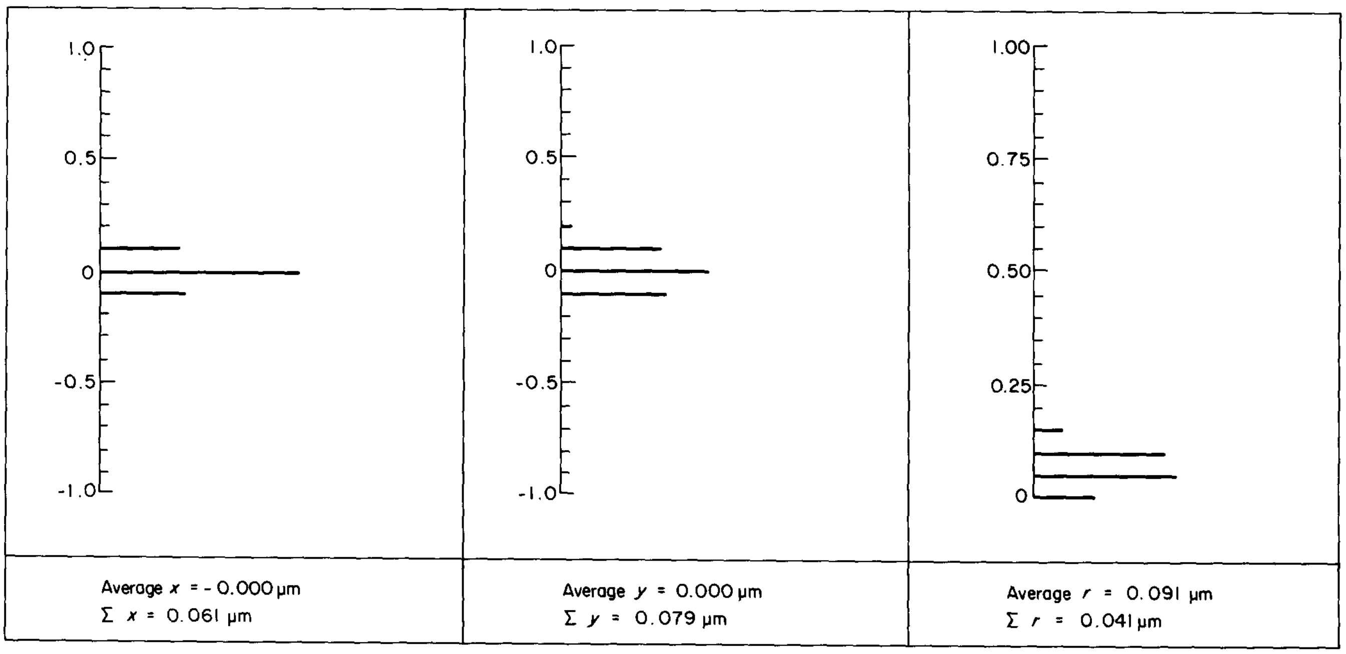

Fig 12 Working array statistics

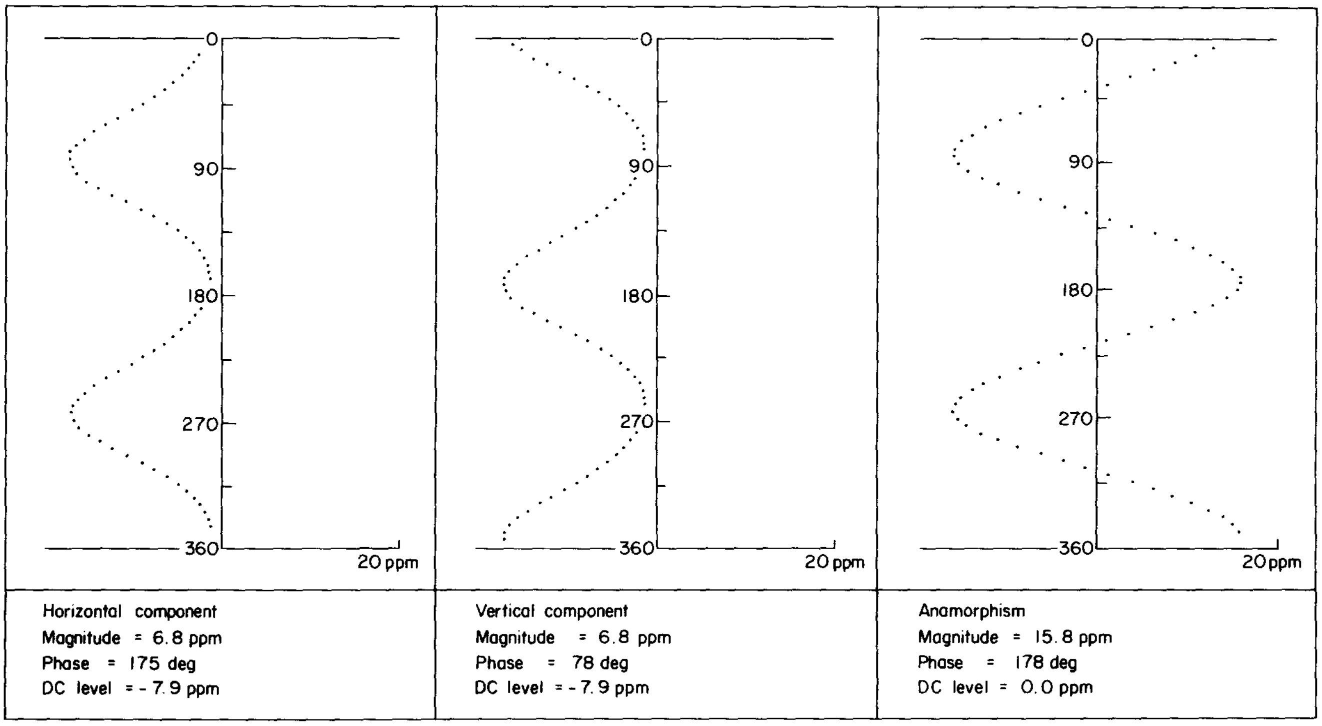

Fig 13 Lens anamorphism errors

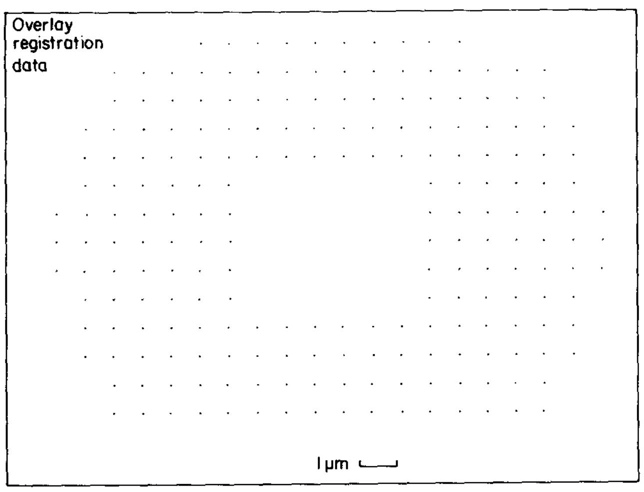

Fig 14 Overlay of first and second lenses to 0.18 μm specification. (All points are within specification)

particularly the technique developed using electrical structures to match both stepper lenses and stages. This development provides the ability to identify correctable and uncorrectable lens errors and hence allow volume production using a number of matched exposure systems.

Overall, the technology issues discussed throughout are justified by the fact that T800s are run successfully on matched steppers to the required specifications.

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