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NEW OR IMPROVED DEVICES.

DIRECT STEPPING ON WAFERS

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Résumé. — Le phénomène d'ondes stationnaires dans une résine couchée sur un substrat réflecteur conduit, lorsque l'épaisseur de résine varie, à une modulation de la largeur du trait que l'on veut reproduire par projection. Nous nous attachons à mettre en évidence l'influence de paramètres tels que la réflectivité du substrat, l'ouverture numérique de l'objectif utilisé, le degré de cohérence spatiale de la lumière, l'épaisseur de résine et leur effet sur cette modulation.

Nous montrons qu'il est possible de transférer sur un substrat fortement réflecteur tel que l'Al des traits de 1 μm au passage de marches de 0,5 μm avec l'objectif CERCO TULIPE 5 X à condition d'utiliser une forte épaisseur de résine $\simeq$ 2 μm et un éclairage spatialement cohérent.

Abstract. — Standing waves phenomena in a resist laid on a reflective substrate give rise, when resist thickness changes, to variations of linewidths to be transferred by projection printing.

We have attempted to display all parameters such as wafer reflectivity, numerical aperture of the lens, spatial coherence of illumination, resist thickness, and their effect on linewidth variations.

We demonstrate the possibility to transfer, onto a strongly reflective substrate such as aluminium, lines and spaces 1 μm wide over steps 0.5 μm high, through a CERCO 5 X TULIPE lens, if the resist layer is $\simeq$ 2 μm thick, and if the illumination is spatially coherent.

1. **Introduction.** — Direct stepping on wafers has become a well-known and accepted technique after many recent publications [1-5].

New machines appear, in laboratories or on the market, with a few or many automatic adjustments, production-oriented [4], [6], [7].

Compared with stepping on masks, the new technique requires two additional know-how : automatic alignment and transfer of small linewidths in a resist laid on reflective substrates with relief structures.

On these substrates, the thickness variations of the resist near the steps gives rise to linewidth variations altering the electrical characteristics of the devices. D. W. Widmann and H. Binder [2] have presented a model that displays the phenomena occurring then in the resist.

We are going to demonstrate, by starting from this model and considering the image formation process in thick resist, the adequate way to transfer linewidths in the 1 micrometer range whatever the wafer material, including the worse case when the wafer is covered with aluminum.

Our experimental instrument was a production step and repeat camera (JADE Microstep 440) equipped with a CERCO 5 X TULIPE lens ($\lambda = 405$ nm ; $N.A. = 0.30$; $\varnothing$ 14 mm), in which we have replaced masks by wafers.

2. **Light intensity distribution in the resist layer.** — The calculation of light intensity existing in the resist allows understanding of exposure phenomena near the steps where strong variations of resist thickness appear. This calculation has been performed by many authors [1], [2], [5].

We refer to it again when considering a resist layer (AZ 1350 H) of refractive index n_R, laid on a wafer coated with aluminum of refractive index n_A and exposed to a monochromatic plane wave of wavelength $\lambda = 0.4047$ μm. This plane wave, when reflected by the aluminium substrate, gives rise to standing waves. This phenomenon is an effect of temporal coherence, caused by the fact that resist thicknesses are generally smaller than the coherence length $\lambda^2/\Delta\lambda$.

We obtain a quasi periodic intensity distribution within the resist, whose period is $\lambda/2\,n_R$. This dis-

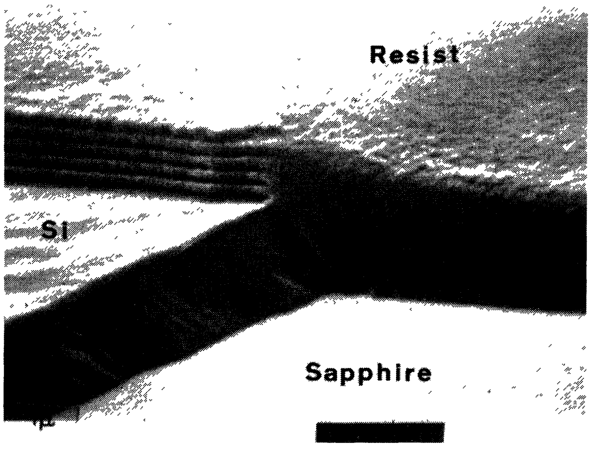

FIG. 1. — Sample : Silicon on sapphire. Standing waves in resist on reflective substrate : silicon. No standing waves in resist on non reflective substrate : sapphire.

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tribution appears in the wavy profile of the resist edge after development, displaying the maximum and minimum intensity planes. If the substrate is not reflective, standing waves do not appear (Fig. 1).

We observe a strong variation of the average

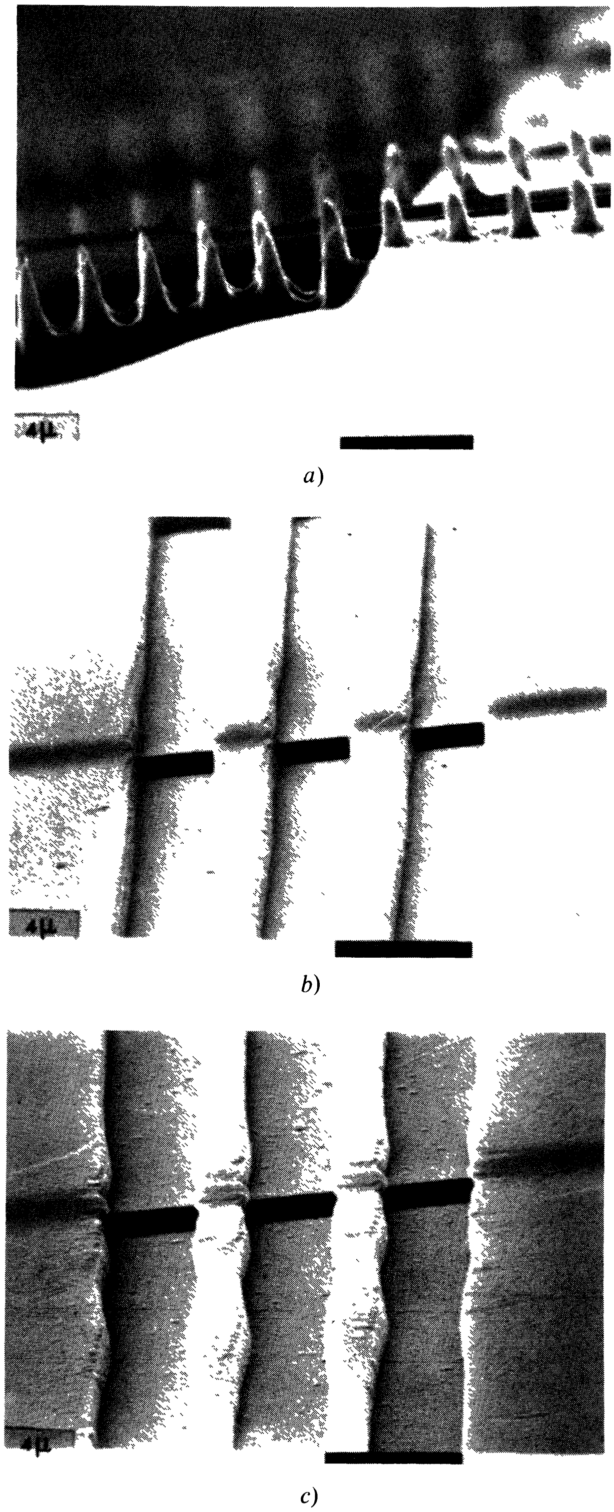


FIG. 2. — Linewidth variations *versus* substrate reflectivity : *a*) Substrate glass — 0 % reflectivity : no linewidth variations. *b*) Substrate silicon — 40 % reflectivity : light linewidth variations. *c*) Substrate aluminum — 90 % reflectivity : strong linewidth variations.

intensity in the resist for a thickness variation of about 0.05 μm. These intensity variations are quasi periodic functions of resist thickness. Therefore when a line is projected onto a surface presenting changes in resist thickness, for instance near the steps, adjacent areas are respectively overexposed and underexposed, giving rise to linewidth variations.

The observed variation increases with the standing waves amplitude, i.e. with the wafer reflectivity (Fig. 2).

3. **Image formation.** — It must be noticed yet that intensity variations existing in the resist, depending upon its thickness, would not produce changes in linewidths if the light distribution in the image plane was conform to the object transmission. For a periodic object, the light distribution in the image plane would be represented by a square wave function ; then the developed linewidth would be independent of the average intensity variations in the resist.

In fact the light distribution in the image plane is not exactly conform to the object : a continuous transition appears, from dark to light areas. Let us consider a periodic object illuminated by a collimated beam.

If the collimation angle of the beam is much wider than the first order diffraction angle of the periodic object, i.e. for an extended source or an object of low spatial frequency, the illumination is spatially incoherent : the object to image correspondence is described by the modulation transfer function of the lens. The intensity distribution is then the sum of intensities of spatial frequencies transferred by the lens. When the spatial period p' of the image is near the best practical resolution of the lens on resist :

$$p' \simeq \lambda/N.A. \Leftrightarrow MTF \simeq 40\,\%$$

only the fundamental period of the object is transferred, and the intensity distribution in the image plane has a sine profile. Then the linewidth variation is maximum.

If the collimation angle α of the beam, or half-angle between extreme illumination wavefronts, becomes smaller than the first order diffraction angle λ/p of the object, phase relationships appear between points of the object, displayed by a discrete spectrum, visible in the Fourier plane of the lens, and composed of small spots S_0, S_1, S_{-1}, etc. (Fig. 3), the illumination is spatially coherent; this is easier to achieve with smaller reduction ratios. Wavefronts issued from these spots interfere in the image space, building a periodic image of the periodic object by a process similar to generation of holographic gratings, but using three or more wavefronts instead of two. The image within the resist layer is then generated by standing waves normal to the wafer : thus are explained vertical profiles obtained after resist development.

The fundamental spatial frequency is generated by interference of Σ_1 and Σ_{-1} with Σ_0, and the double

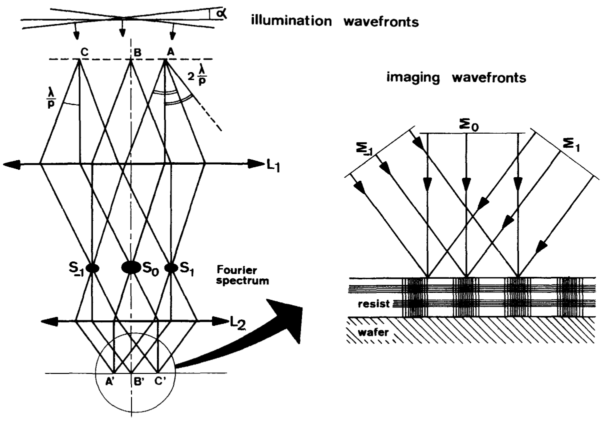
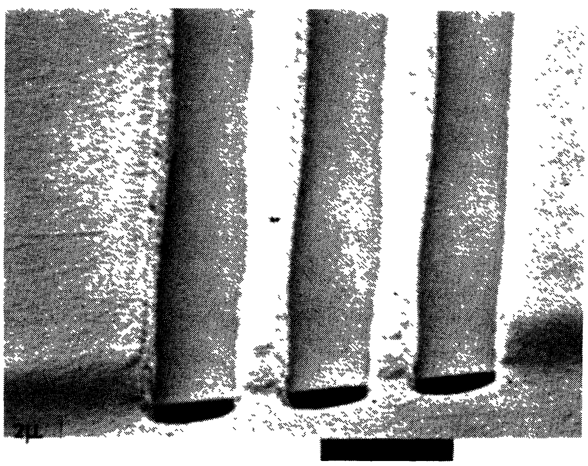


FIG. 3. — Image formation in thick resist. Wave fronts Σ_0, Σ_1, Σ_{-1} issued from the discrete spectrum S_0, S_1, S_{-1} in the Fourier plane interfere in the image space building a standing waves sytem normal to the wafer.

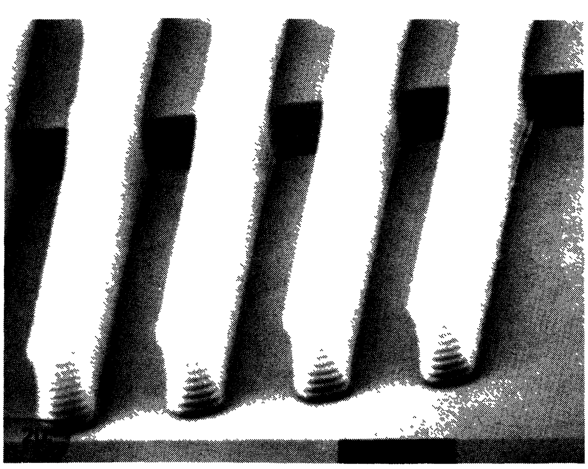
frequency is generated by interference of Σ_1 with Σ_{-1}. Therefore the intensity distribution in the image plane is always closer to a square wave function than to a sine profile, as soon as an image exists, i.e. for $p' > \lambda/N.A.$

Therefore under spatially coherent illumination, linewidth variations are smaller than under spatially incoherent illumination.

In both situations, in order to reduce the wrong influence of resist thickness variations, a large numerical aperture is wanted, allowing the transfer of high spatial frequencies giving rise to a profile close to the square wave function (Fig. 4).



a)



b)

FIG. 4. — Linewidth variations *versus* numerical aperture. *a)* Substrate Si/SiO$_2$ — linewidth 1 µm. Objective ZEISS 10 X *N.A.* = 0.28. *b)* Same substrate — linewidth 0.9 µm. Objective CERCO APONAR 20 X *N.A.* = 0.48. A large numerical aperture gives rise to lower linewidth variations.

4. **Development phenomena.** — To describe the developer action, we start form the same assumption as D. W. Widmann and H. Binder [2] : the rate of photoresist removal in the developer at a given point in the resist is proportional to the light intensity $I(x, y, z)$ that was previously at this point.

Considering the developer action along the only z direction, our assumption becomes :

$$\frac{dz}{dt} \alpha I(x, y, z) = I_0(x, y) f(z) .$$

This expression, when knowing $I(x, y, z)$, gives the development time necessary for a resist thickness d :

$$T_d \alpha \frac{1}{I_0(x, y)} \int_0^d \frac{dz}{f(z)} = \frac{A(d)}{I_0(x, y)} .$$

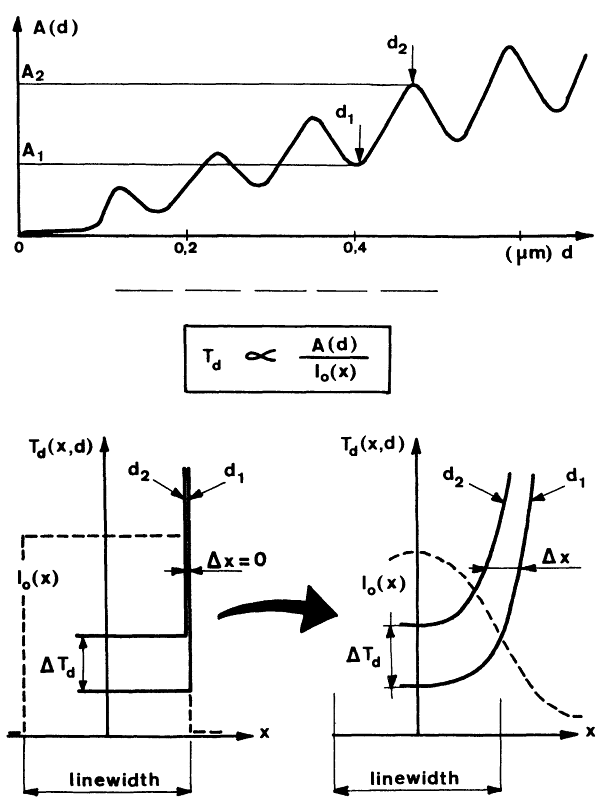


FIG. 5. — Development time *versus* resist thickness and linewidth. $A(d)$ exhibits the quasi periodic maxima and minima due to standing waves. Down left : for a steep variation of $I_0(x)$ in the image plane : no linewidth variation ($\Delta x = 0$). Down right : $I_0(x)$ has a sine profile due to low resolution (incoherent illumination) : linewidth variations ($\Delta x \neq 0$).

The development time is function of the resist thickness d and of the intensity distribution in the image plane, $I_0(x, y)$ (Fig. 5).

$A(d)$ exhibits the quasi-periodic maxima and minima due to standing waves.

Let us assume a steep variation of $I_0(x)$ in image plane (Fig. 5 down left) : no linewidth variation appears if the development time is longer than the time necessary to dissolve the resist thickness d_2.

In this way the model displays the assumptions of § 3. The linewidth variation Δx (Fig. 5 down right) is caused by the continuous transition of $I_0(x)$ from dark to light areas ; this transition and the sine profile of $I_0(x)$ come from the low resolution (§ 3 incoherent illumination).

Then curves giving development times for two *thicknesses* $T_d(x, d_1)$ and $T_d(x, d_2)$ are separated and the deviation Δx measured for a given development time is the half-linewidth variation when the resist thickness changes from d_1 to d_2.

We notice first that Δx decreases when T_d increases. Secondly the relative variation $\Delta T_d / T_d$ decreases rapidly when resist thickness grows ; then curves $T_d(x, d_1)$, $T_d(x, d_2)$ come closer to one another and Δx decreases. Consequently, thicker resist layers display smaller linewidth variations.

5. **Experimental results.** — Practically, for a given lens, the maximum useful resist thickness has to be found, for a required linewidth.

This can be experimentally achieved, by imaging on a thick resist a test including a sequence of periodic objects, from $\lambda / N.A.$ up (Fig. 6).

The CERCO 5 X [3] lens, under a spatially coherent illumination, allows the transfer of 0.6 μm lines and spaces all over the 1 cm^2 field. The experiment has been performed on a glass substrate, coated with AZ 1350 H 4 μm thick. This gives an evaluation of practical resolution *versus* resist thickness ; as an example, it is possible to transfer 1 μm lines and spaces in a resist layer 2.5 μm thick (Fig. 6).

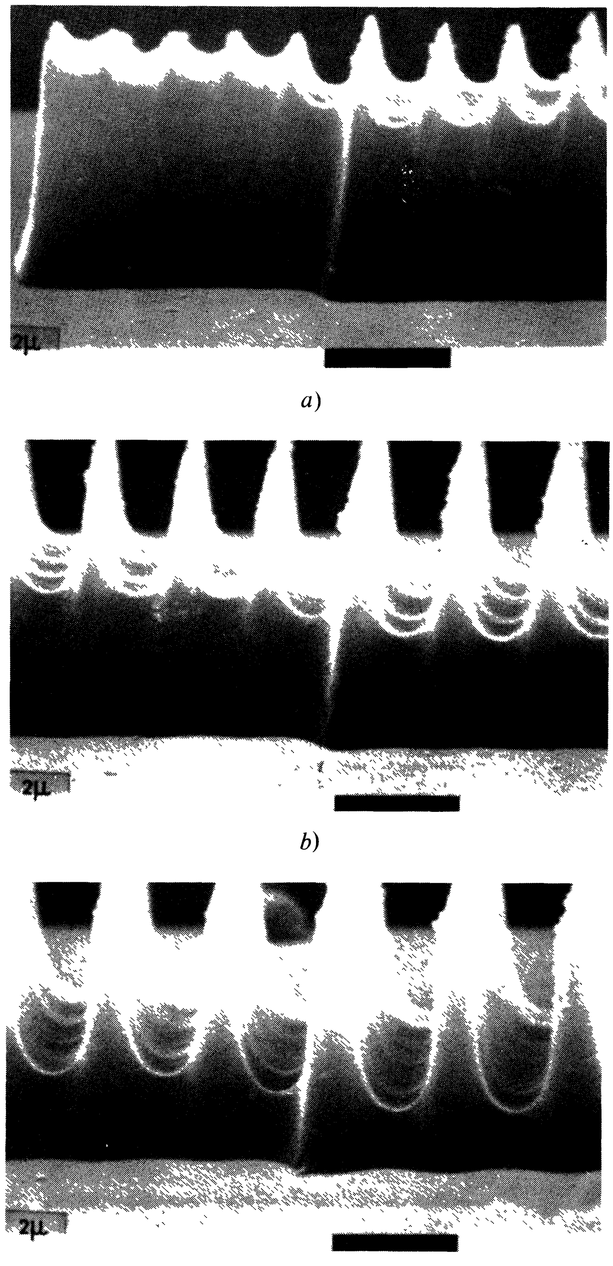


FIG. 6. — Developed depth in resist *versus* linewidth. Periodic object of linewidth from 0.5 μm to 1 μm. It is possible to transfer 1 μm lines and spaces in a resist layer 2.5 μm thick.

This result has led us to examine the influence of high resist thicknesses on linewidth variations, across aluminum steps. Results, in good agreement with the model, display decreasing linewidth variations when the resist becomes thicker (Fig. 7 left).

Variations smaller than 20 % are obtained for linewidths in the 1 μm range if the resist is about 2 μm thick (Fig. 7 right).

Practical minimum linewidth to be transferred by direct stepping under production requirements onto reflective wafers with steps is about twice the minimum linewidth achievable on flat non-reflective wafers. In our example this useful linewidth is 1.2 μm on aluminum.

6. **Conclusions.** — Finally our results have shown a good agreement with the starting models :

— Spatially coherent imagery explains the vertical profiles of developed resist.

— Linewidth variations increase with the wafer reflectivity, decreases with high numerical apertures, with a spatially coherent illumination and for a thicker resist, in good agreement with the model and conclusions of D. W. Widmann and J. Binder.

These results demonstrate optical projection in the step and repeat mode as being presently a real industrial way for the transfer on any kind of substrate : reflective or not, flat or with relief, of patterns in the micrometer range.

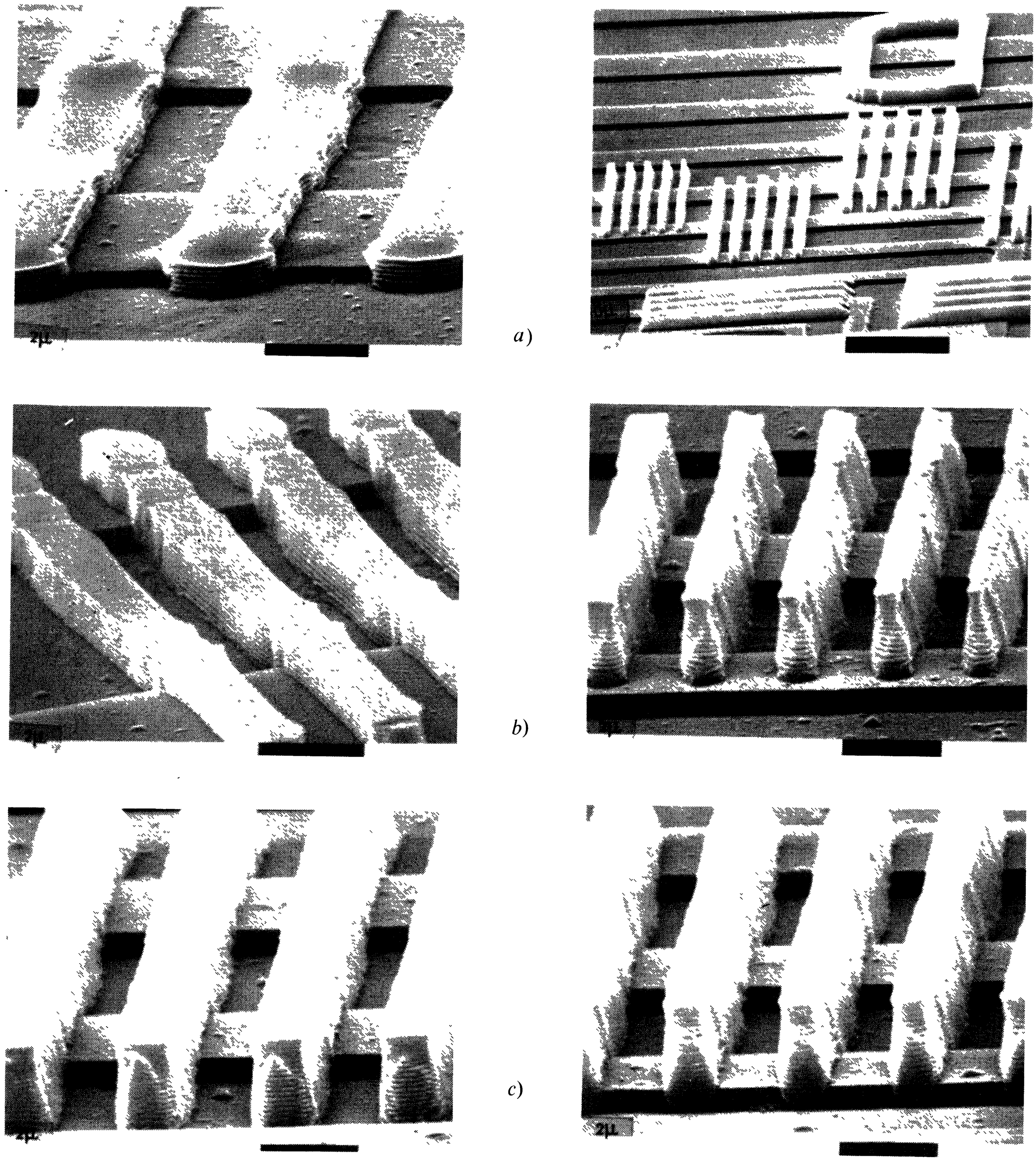


FIG. 7. — Left : linewidth variations *versus* resist thickness on aluminum steps : *a*) Resist thickness : 0.6 μm — linewidth 2 μm. *b*) Resist thickness : 1.2 μm — linewidth 1.2 μm. *c*) Resist thickness : 1.8 μm — linewidth 1.4 μm.
Right : results on aluminum with steps 0.5 μm high. *a*) General view of the patterns. *b*) 1 μm linewidth. *c*) Practical minimum linewidth 1.2 μm with linewidth variations smaller than 20 %.

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