Silicon die self-alignment on a wafer: stable and unstable modes

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ABSTRACT

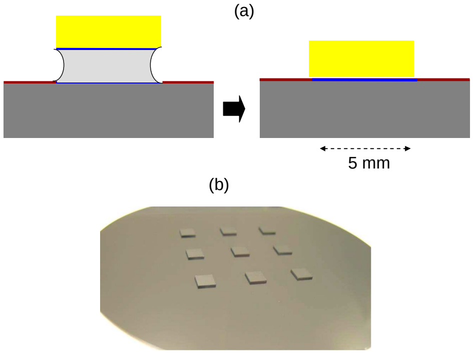
In order to create advanced microsystems by 3D integration, die-to-wafer assembly is foreseen to obtain fast and reliable packaging. Self-assembly methods are promising due to their serial aspect which overcomes the main difficulties of the current techniques. The aim of this work is to understand the mechanisms of self alignment with an evaporating droplet technique and investigate the stable and unstable modes. Using the Surface Evolver software, we analyze the causes for misalignments of the system and their evolution.

Keywords: self-alignment, misalignment silicon die, surface energy minimization.

1 INTRODUCTION

Integration of components on a wafer is needed to obtain a fast and reliable packaging. Self-assembly methods are promising due to their parallel aspect which overcomes the main difficulties of the current techniques. In this work we focus on the self alignment of dies using droplets deposited on specific hydrophilic locations on the wafer. Evaporation of the liquid droplet eventually leads to contact and direct bonding of the die on the substrate [1-4]. This technique allows for self alignment and assembly without any intermediate layer. The bonding strength is high enough so that the assembly can handle post processing, such as thinning down or through-via etching for interconnects.

More specifically, our goal is to understand in details the mechanisms of self alignment and investigate the stable and unstable displacement modes. Because the governing force on the die is the capillary force exerted by the liquid-air interface, the Surface Evolver software is well adapted for this analysis and to the prediction of the response of the system to misalignments and its evolution, e.g. if the die re-aligns [5]. In a first step, the die is gently dropped on a water droplet sitting on a square hydrophilic patch patterned on the wafer surface. At this point, three physical phenomena govern the die motion: (i) evaporation of the water that progressively moves the die towards the wafer surface, (ii) water-air interfacial forces that are expected to bring the die in an aligned position above its planned final location on the wafer, (iii) the weight of the die, but this weight is generally small, often less than 0.05 grams.



5x5 mm² aligned and bonded dies on Si substrate

Fig.1. Principle of die self-alignment: (a) sketch of the die on the droplet and its location after evaporation; (b) view of aligned dies on a wafer.

The experimental setup is composed of dies on top of water droplets deposited on delimited regions of a substrate (fig.1). The 5 x 5 mm² square silicon surface area of the die is super hydrophilic, with a water contact angle lower than 2°. The substrate binding zone has the same size, is also hydrophilic and surrounded by hydrophobic regions.

In previous publications [6,7], the possible reasons for misalignments have been investigated experimentally. We investigate here the self alignment mechanism of the die on the wafer with the help of numerical simulation.

2 PHYSICAL ANALYSIS

In the following, we focus on the capillary forces on the die. Evaporation is not taken into account in the present work, e.g. evaporation is supposed to have a characteristic time much larger than that of the capillary motion. The displacement of the die is then governed by capillary forces linked to the minimization of the liquid surface area [8].

We use the Surface Evolver numerical software to follow the displacement of the die towards its stable position minimizing the surface energy, which, in this precise case, is the same as minimizing the interfacial area [5]. Remark that the contact angle do not intervene in the model because the droplet is pinned on the die edges on one side, and on the contour line of the hydrophilic patch on the other side.

Four different displacement modes can be identified (fig.2): (1) the lift corresponding to a vertical motion of the plate, (2) the twist corresponding to a rotation of the plate in the horizontal plane, (3) the shift which is a horizontal translation of the plate, and (4) the tilt which is a rotation of horizontal axis.

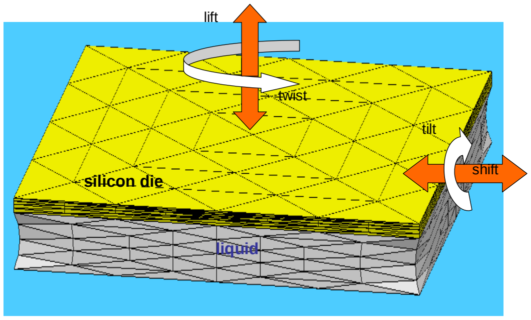


Fig.2. The four different types of misalignment: lift, twist, shift and tilt.

We investigate successively these four modes and check if each of these modes brings back the die in an aligned position.

2.1. First mode: horizontal displacement (shift)

Let us note γ the surface tension, a the side length of the die, S the interfacial area, and V the liquid volume. The first displacement mode corresponds to a horizontal shift of the die. It is obvious that the surface area is larger after a shift. Surface Evolver shows that strong capillary forces pull back the die into alignment (fig.3). The force along the horizontal direction x is given by

$$F_x = -\frac{\partial(\gamma S)}{\partial x} \qquad (1)$$

Figure 4 shows the values of the back pulling force for different liquid gaps. In the case of small shifts, this force is larger for small gaps because of the larger relative change of interfacial surface area.

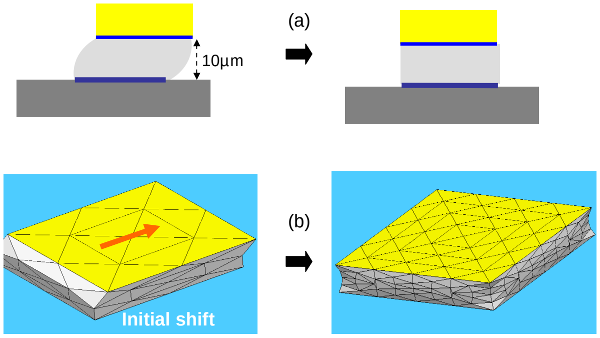


Fig.3. (a) After a horizontal displacement, the die is pulled back to alignment by capillary forces; (b) Evolver calculation of the back pulling.

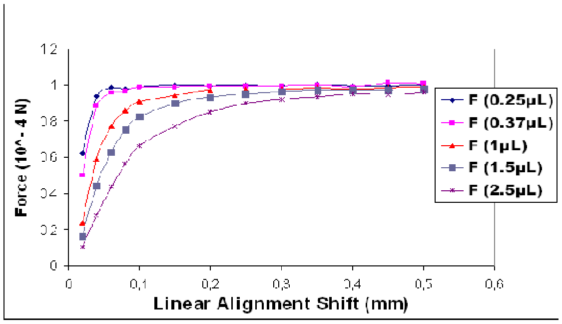


Fig.4. Back pulling force vs. shift for different values of the droplet volume.

2.2. Second mode: twist

A twist is a rotation of vertical axis. In this case too, a twist contributes to increase the interfacial area, and the die is pulled back to alignment, as shown in figure 5.

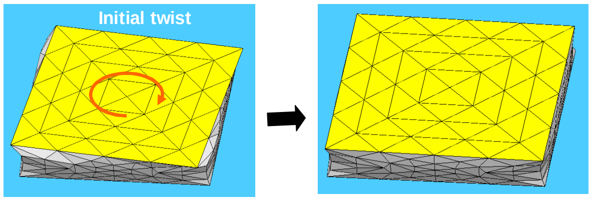


Fig.5. Die realigns after an initial twist.

The torque on the die is given by

$$T = -\frac{\partial(\gamma S)}{\partial(\alpha)} \qquad (2)$$

The torque is plotted on figure 6 as a function of the twist angle using (2) on 3rd order polynomial fitting the Evolver results.

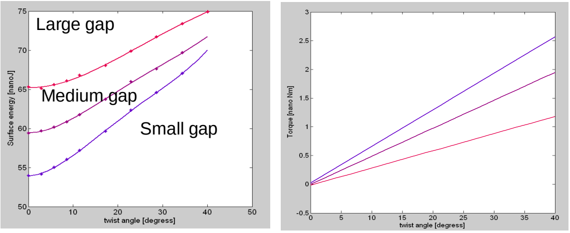


Fig.5. Energy and torque as functions of the twist angle, for two values of the gap ("large gap" corresponds to a ratio gap-chip size of 0.16, "medium gap" to 0.1 and "small gap" to 0.04)

2.3. Third mode: vertical displacement (lift)

Because the vertical location of the die is a balance between gravity and capillary forces, it is expected that there is only one stable height for the die. This is confirmed by the numerical simulation.

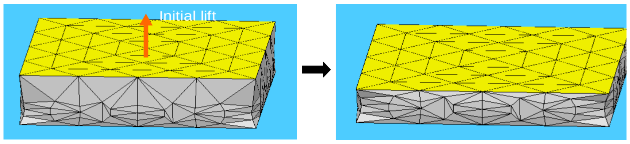


Fig.6. Die regains its stable position after a lift.

2.4. Fourth mode: tilt (or roll)

Tilt (or roll) is a much more complex because the variation of the interfacial area is more difficult to apprehend. If we make the very simple calculation depicted in figure 7, we deduce that the problem is indeterminate. For the same volume of the same liquid, assuming the simplest form of interfaces, the surface energy in a flat configuration is

$$E=\gamma S=\gamma(4\,a\,h)=\gamma\left(4\frac{V}{a}\right) \tag{3}$$

where V is the liquid volume. In a dihedral morphology, the surface energy is

$$E=\gamma S=\gamma\left[2\left(\frac{\alpha a^2}{2}\right)+\alpha a^2\right]=\gamma\left(4\frac{V}{a}\right) \tag{4}$$

Hence, it is the distortion of the interfaces that can make the difference and pinpoint the stable position. It is a second order problem. This remark leads to serious complications: on a numerical standpoint, the meshing of the surface should be sufficiently fine to produce a precise value of the energy. In return, the computation time is very long. On a physical standpoint, the role of the parameters—like the weight of the die, or the surface tension of the liquid—is difficult to apprehend.

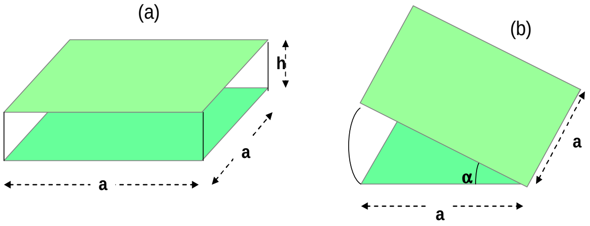


Fig.7. Two morphologies of the liquid having the same surface energy.

The calculation shows that the corner position (b in figure 7) is the stable position whatever the initial depth of the liquid gap (fig.8).

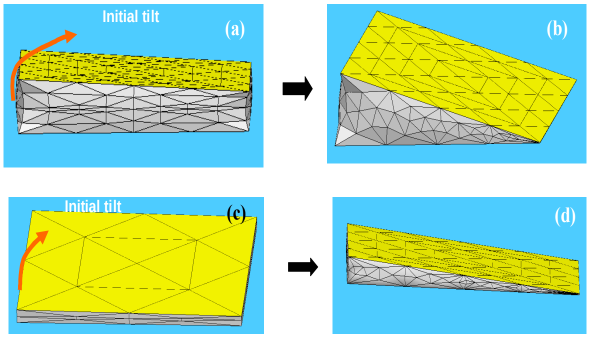


Fig.8. Die slides to form a dihedral: (a) and (b) large liquid volume; (c) and (d) small liquid volume.

The slightly smaller interfacial area for the dihedral morphology is due to small distortions of the interface in the die corners and along the die sides. The interface is concave in the first regions, and convex in the others (fig. 9). Parallel die-wafer morphology has 4 concave and 4 convex distortions, whereas the dihedral die-wafer morphology has only 2 concave and 3 convex distortions.

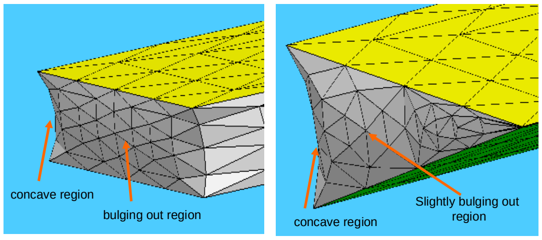


Fig.9. Bulging out/in shape of the interface in the two cases.

3 DISCUSSION AND CONCLUSIONS

Of all the four modes, only the tilt (roll) is slightly unstable. However, this later mode does not disrupt necessarily the die alignment. First, if the dihedral is well formed, as shown in figure 8, the evaporation will bring the die in perfect alignment. Second, the tilt-motion mode is slow if the die weight is small; evaporation might proceed before the dihedral is completely formed.

Note that the weight of the die (and the volume of the droplet) is an important parameter at this stage. Let us take the extreme case of a large droplet and a heavy die (values that are out of the range of our problem). It can be shown that the die slides on the droplet surface (fig. 10). This has two consequences: first, a perfect aligned corner might not be formed; second, liquid can be drained out of the hydrophilic region on the wafer. Each phenomenon leads to misalignment. Of course, in the real case the droplet is much smaller and the die is very light (less than 0.03 grams), nevertheless that could be the reason for some observed misalignments.

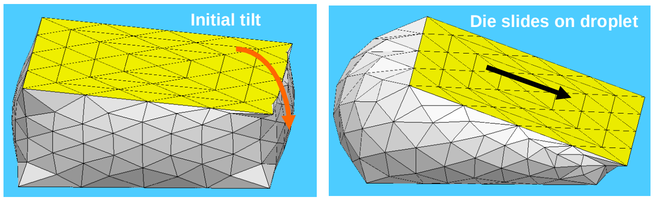


Fig.10. Heavy die slides on the droplet surface after a tilt.

De-pinning might also be a problem for alignment: if the liquid overflows on the hydrophobic surface, the alignment has no reasons to be good. Curiously, de-pinning has the property to be stable to tilt, allowing the die to regain horizontality, as shown in figure 11.

In conclusion, die self-alignment using patterning and droplet evaporation is a promising technique (fig. 12). Shift, lift and twist misalignments are prevented by the capillary forces. Tilt misalignment is slightly unstable, but, under the condition that the die is light enough and the liquid volume small, the die will eventually form a receding dihedral aligned with the wafer. A strong hydrophilic-hydrophobic contrast is needed to prevent liquid overflow. The next logical step is taking into account of the evaporation.

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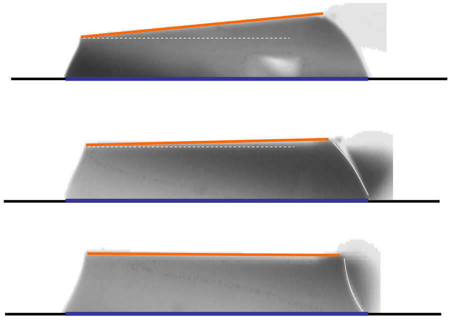

Fig.11. After a 0.1 radian roll, the die comes back into horizontal position just because the liquid has over flown on the hydrophobic surface. This expansion allows the die regain horizontality.

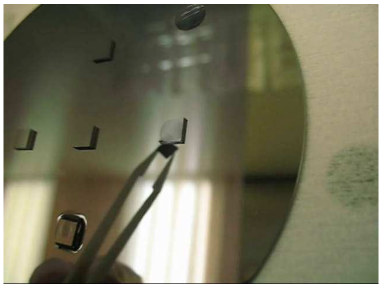

Fig.12. Dies aligned on a wafer.