In-house bump bonding

July 12, 2012

The CMS DPIX Group

Introduction

Bump-bonding is the defining process for the assembly of hybrid pixel detectors, both in terms of technology and in terms of cost. The present barrel pixel detector used Indium bump bonding developed in-house at PSI, while the forward pixel detector relied on external facilities, one of which was the Fraunhofer IZM in Berlin, where also parts of the ATLAS pixel detector were bonded using a SnPb process.The other part of the ATLAS pixel detector was bonded by Selex using Indium. Finally the ALICE pixel detector was bonded by VTT using SnPb.

In 2010 IZM quoted us a price of 2.3 cents EUR per bump for series production (SnAg bump deposition, flip chip bonding, visual inspection), which for 768 modules in the 4th layer (including 50% spares and later rejects) and 66'560 bonds per module amounts to 1.176 MEUR, dominating the costs for ROCs, sensors, and HDIs by a factor of 2. We thus looked for alternatives.

The bump bonding process can be divided into 3 steps: under-bump metal (UBM) deposition, solder sphere deposition, and flip chip bonding with re-flow soldering followed by the bare-module electrical tests. The possibility of replacing individual ROCs at this stage might be desirable to increase the module yield. Dedicated equipment and skilled personnel is required for each step.

Before one starts it has to be realized that the yield depends critically on the metallization quality of the incoming sensor and ROC wafers. There must be no passivation residue on the metal pads and no pinhole-like defect in the passivation layer itself. Visual inspection is required on each batch if not on each wafer. The metal composition can be varied from pure Al to Al-Si and Al-Si-Cu, where different bump bond results have been reported for MediPix modules [1]. DESY and KIT have received wafers of barrel pixel sensors from CIS (Erfurt) with Al-Si and Al-Si-Cu metallization, which was also tried in the first test productions.

For under-bump metallization a simple electroless plating process may be used, which does not require any photolithography or etching, but where the wafers are simply dipped in a bath and the metal grows on all open metal pads. In the course of our tests at PacTech [2] the UBM has been optimized to Ni-Pd-Au (ENEPIG: electroless Nickel - electroless Palladium - immersion Gold) for best yield. The UBM may also be directly deposited at the sensor manufacturer, reducing the transport overhead. For the ROC wafers from IBM an UBM source has to be found anyhow. For the small pad openings on the ROCs (15 μm diameter) the UBM deposition process at PacTech has to be adjusted for smooth infiltration of the smaller volumes, but certification is planned and 12 wafers of the test structures we have ordered from VTT in Finland are already dedicated as setup wafers for that purpose. Openings of 30 μm diameter are routinely processed with good uniformity. After UBM deposition on full wafer batches PacTech also offers further wafer process services of backside grinding, dicing, rinsing, plasma cleaning and singulation into waffle or gel packs. All process steps except grinding were already utilized for the production of test samples.

For step 2 (bump ball deposition) the company PacTech offers a unique machine (SB^2 Jet [3]) that individually places pre-formed balls over the sensor pads and re-flow solders them using a short laser pulse through a capillary. This can be performed on full wafers or on singulated and tested sensors. Alternatively, external vendors were identified for step 2, typically involving photolithography, sputtering, and etching. In this case, bump deposition will be commissioned at an external vendor, while the flip-chip bonding (step 3, see below) is performed in-house. Fraunhofer IZM declined to offer the bump deposition alone, whereas VTT and SELEX (Italy) offer this single process step. Our test structure order at VTT includes the formation of SnPb spheres on some structures. Additional test structures with indium spheres from SELEX are also planned. Results from both vendors are expected in autumn. It should be noted that both, VTT and SELEX, deposit bumps on both counterparts (sensors and ROCs) as a standard procedure.

Step 3 (flip chip bonding) requires another machine of which several with the needed precision ($< 3\,\mu$m) are on the market and have been evaluated. In contrast to the PSI process, this process is now divided into two steps: flip chip placement with thermally assisted tacking by force of individual ROCs on the sensor followed by re-flow soldering of the full module. Just before, the ROCs should undergo a final known-good-die electrical test, which requires a probe needle card and a PSI46 testboard integrated with the machine. The heat for re-flow soldering may be applied by a laser pulse (PacTech LaPlace) or in a thermal chamber, preferrably in a reducing atmosphere (formic acid vapor), like in the Femto from FineTech [4].

The in-house assembly of modules allows a tighter quality assurance in that the definitive electrical bump yield test on a probe station can be done immediately, whereas the visual inspection using X-ray imaging at IZM gives only partial results. Production quality problems should be detected before a larger number of modules is affected. Purchase of the machines and in-house production gives larger scheduling flexibility and increases the over-all bump bonding capacity for the CMS pixel upgrade considerably.

Test structures

We are investigating the PacTech SB^2 jet since Autumn 2010, first using test structures from PacTech and then full-size test structures with the CMS pixel geometry made at CIS (Erfurt) on 400 μm thick substrates. These structures involve only two masks (metal and passivation openings) and contain chains of 160 bump bond pads arranged in double columns at the $100 \times 150\,\mu$m pitch of the ROC, with contact pads for 4-point resistance measurements at the periphery, see figure 1. A single 4-inch wafer carries two sensor-like and 40 ROC-like structures.

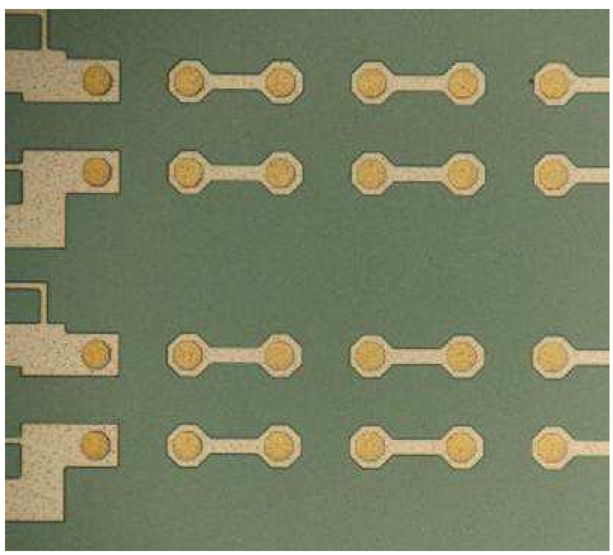

Figure 1: ROC-like test structure showing the beginning of a contact chain to the right and the 4-point probe lines on the left

The passivation opening was increased to 30 μm diameter on both structures. On the real sensor production this should be incorporated in our design while the IBM ROCs will stay with 15 μm openings, for which the UBM process still has to be qualified. One batch of 20 wafers (100 mm diameter) was produced by CIS. The UBM initially desposited at PacTech was electroless Nickel (5 μm) and immersion Gold (50 nm) (ENIG), see figure 2, while now an intermediate Palladium layer (200 nm) (ENEPIG) is added to improve wetting and slow down diffusion of Ni into the Sn-Ag-Cu (SAC) solder.

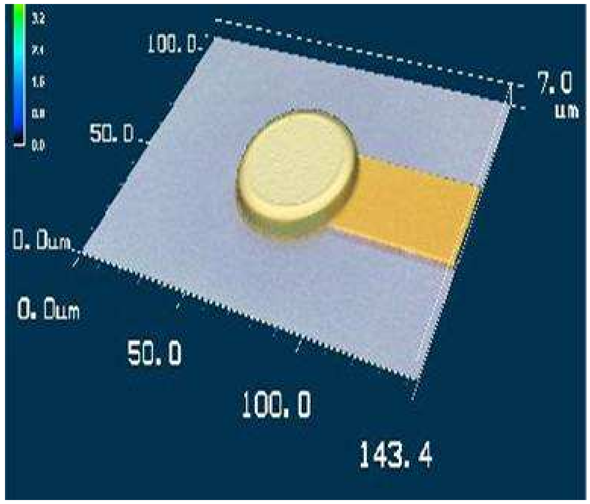

Figure 2: Laser scan image of a pad with 5 μm Ni-Au UBM on a test sample from PacTech

At PacTech, the SB^2 Jet machine was used to place SAC solder balls of 40 μm diameter at a rate of 5 Hz (giving 4 hours per module, our goal). Speed has to be balanced against yield. The dominating failure is missing balls, which is cured by an automated optical inspection and filling of missing spots in a second, much shorter pass. The capillary tip is cleaned automatically after e.g. every 1000 balls from remaining molten solder debris. Another failure is dual ball placement leading to macro bumps. At our pitch and ball size this usually does not create a short to a neighbouring pad. The electrical influence (noise, cross talk) still has to be investigated on the first live samples. This macro bump failure occurs at a rate $\leq 0.1\%$ per chip and is believed not to impact the flip chip process and can probably be reduced by regular exchange of the capillary. About 1.3 M solder balls of 40 μm diameter have been placed so far for us at PacTech. Spheres of 30 μm diameter are in the internal qualification phase. Their use would simply require a smaller capillary and possibly a different singulation unit, both modular parts of the machine.

Sensor-like structures with solder balls were taken to FineTech in Berlin for flip-chip bonding on a Femto machine [4]. In contrast to other machines (SET FC 150, SET Kadett, PacTech LaPlace) the Femto has a bonding arm that only moves up and down, while the platform carrying the sensor and chip tray with ROCs moves by precision step motors. After training, the procedure is fully automatic and much faster than SET machines, with known good die testing, ROC placement and tacking and final reflow heating. The Femto includes detailed data logging of relevant process parameters (position, speed, temperature, force) which should allow precise failure analysis, if needed. FineTech offers a heating chamber with formic acid atmosphere for

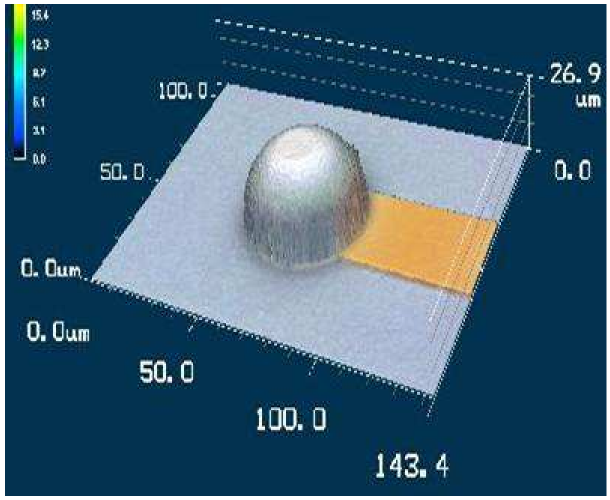

Figure 3: Laser scan image of a pad with 40 μm solder ball placed with the SB^2 Jet on a test structure from PacTech

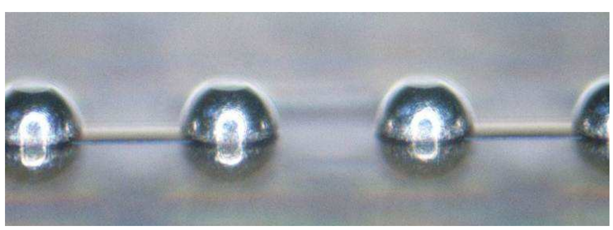

Figure 4: Optical microscope side view of 40 μm solder balls placed with the SB^2 Jet on a contact chain test structure.

in-situ re-flow processes, which can be adapted to suit our needs. Bonding parameters to be optimized include tacking force, temperature and time, base plate temperature, and heating cycle.

Initial samples where taken to DESY for destructive inspection of the bonds (cutting and grinding), see figure 5 and figure 6.

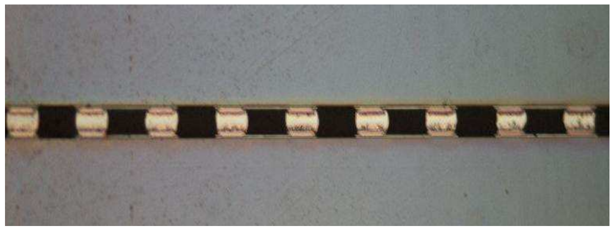

Figure 5: Cross section of 40 μm bump bonds after cutting and grinding. All spheres are nicely re-flown and make good contact.

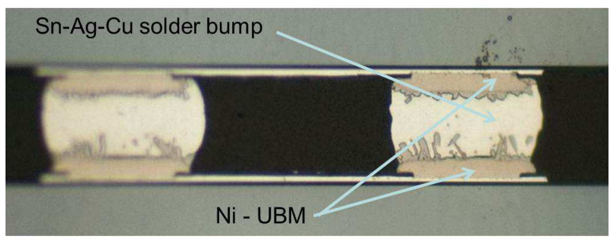

Figure 6: Bump bond cross section after cutting and grinding. These are initial samples with Ni-Au UBM, showing mixing of Ni in the SAC solder sphere (stronger at the bottom, which was re-flown three times). The Pd layer added now reduces the inter-metallic phase development and smoothes the rough Ni surface for better solder wetting.

Results

The shear strength of 40 μm solder balls was measured on PacTech test structures to be 0.21 N/bump, a good value.

Two fully equipped sensor-like structures where brought to DESY for ohmic testing of contact chains on a probe station. A probe card with 104 needles for 4-point contacting of 26 chains per ROC-like structure is used. A current is injected to a chain of 160 bonds and the voltage drop measured.

The distribution of the measured bump resistances is shown in figure 8. The mean chain resistance is 21 Ω, from which 18 Ω due to the connecting metal lines are subtracted. The remaining

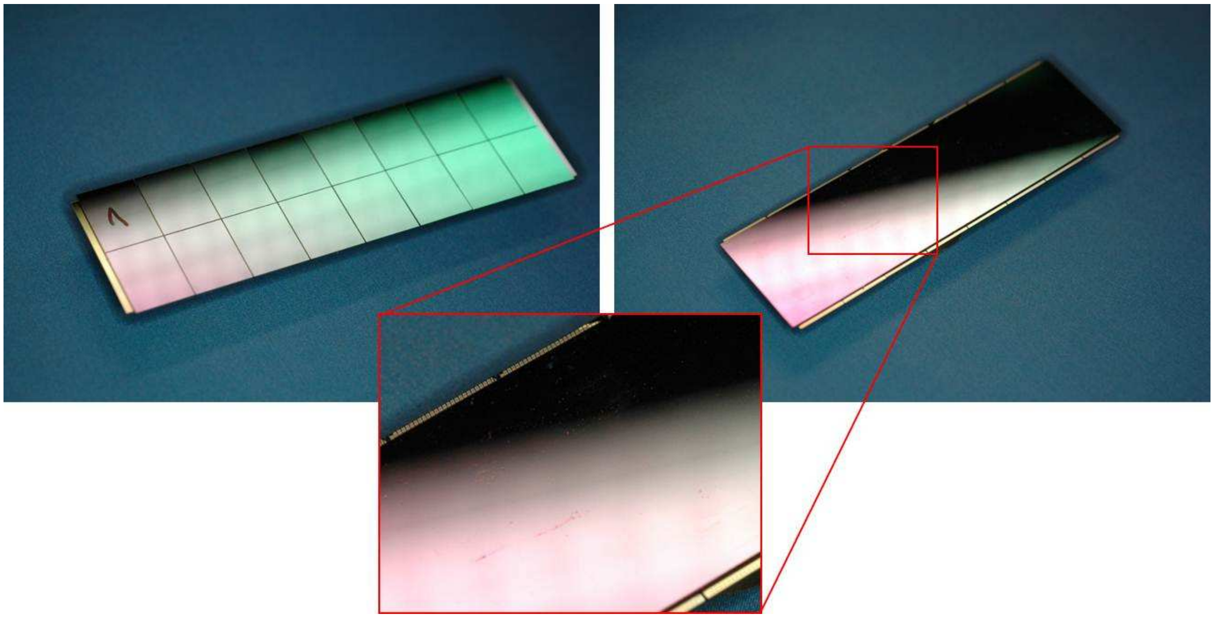

Figure 7: 16 ROC-like structures (top left) bump bonded to a sensor-like strucure (top right) with the probing pads protruding at the periphery (zoomed view, middle).

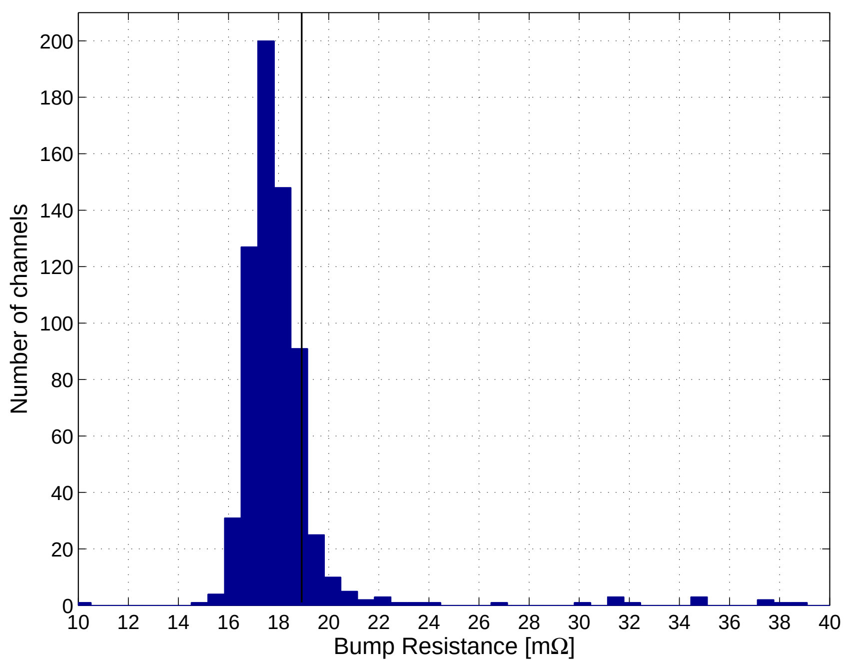

Figure 8: Bump resistance distribution derived from 676 chains with 160 bumps each. The resistance of the interconnecting metal lines is subtracted (it dominates the measurement: $18\,\Omega$ out of $21\,\Omega$ per chain). The mean single bump resistance is $18.9\,\mathrm{m}\Omega$.

mean bump resistance is 18.9 mΩ. The tails in the distribution are due to the learning curve on the first full module, see figure 9, which shows the mean resistance of up to 26 chains per ROC. The first 8 ROCs on Module 1 where used for optimizing parameters of the Femto flip chip bonder; the remaining 24 ROCs where bonded with fixed parameters and give uniform results.

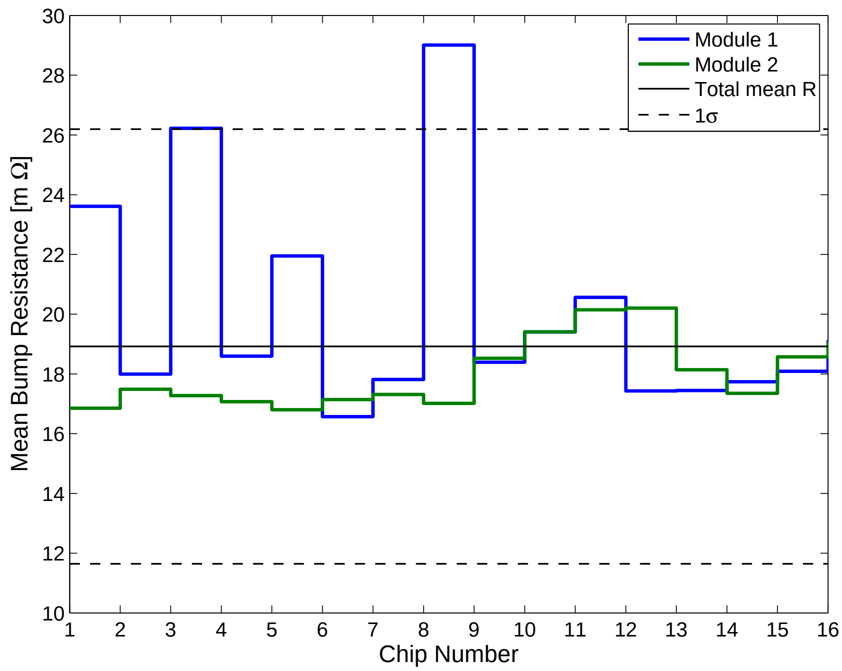

Figure 9: Mean bump bond resistance per ROC for 2 modules. The first 8 ROCs on Module 1 where used to optimize the parameters of the Femto flip chip bonder.

A single missing bump bond leads to a defective chain, which was the case on 156 out of 832 chains (19%). The functional bump yield is therefore close to 99.87%. The distribution of defective chains per ROC is shown in figure 10, where one ROC (on Module 1) is close to the maximum of 26 but the others cluster around 3–4 defects per ROC (0.1%).

Looking at the position of the defective chains per ROC in figure 11, we observe peaks at chain 7, 18, and 26 which might indicate contact problems of the probe card. The bump bond yield might therefore be higher than quoted above.

Further tests

The bump bonded Module 2 has been sent to FZ Jülich for X-ray imaging. Further test structures have been ordered from VTT in Helsinki, this time involving ROC-like structures with

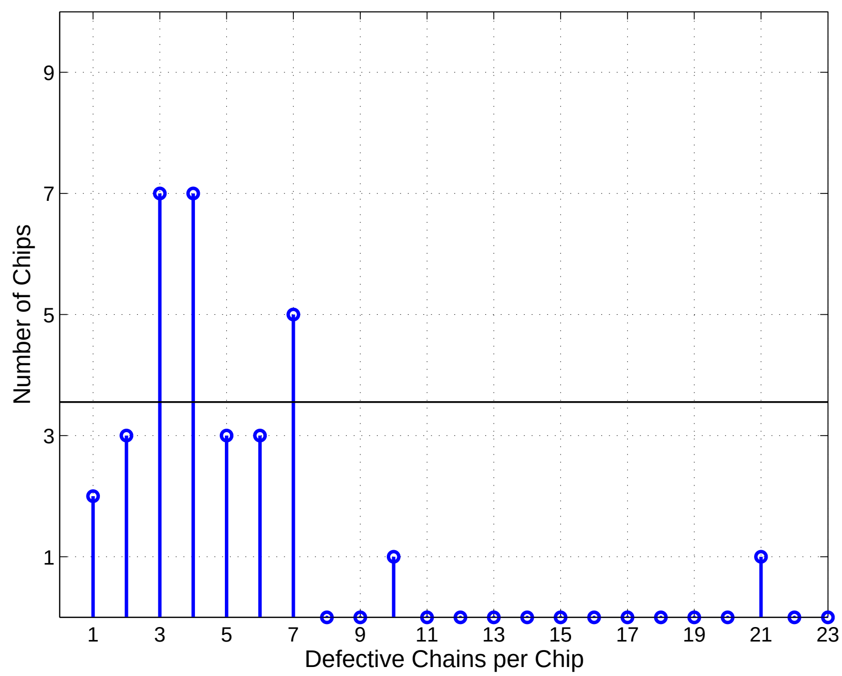

Figure 10: Number of defective chains per ROC-like structure from the first two modules.

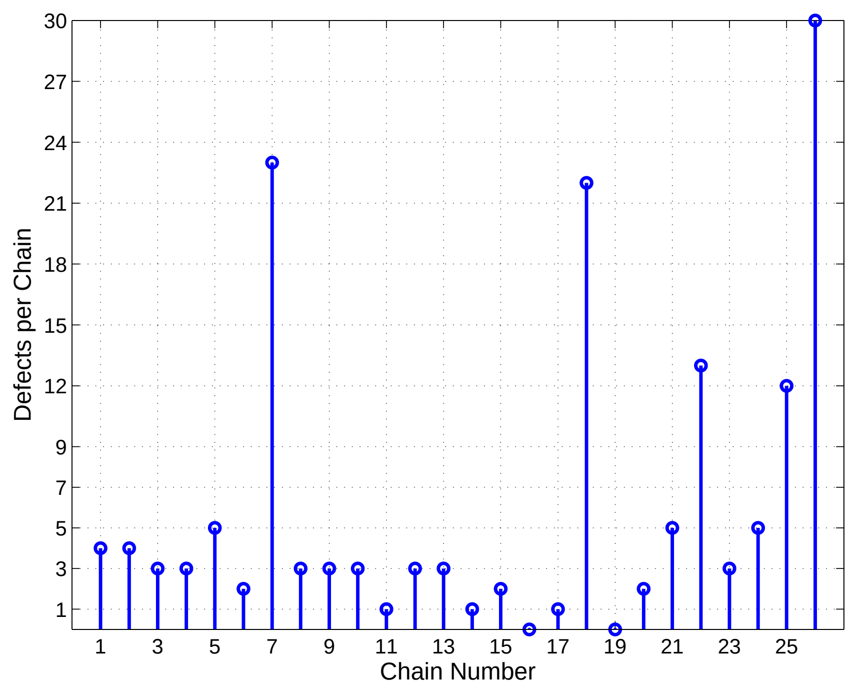

Figure 11: Index of defective chains per ROC-like structure.

nominal passivation openings of 15 μm diameter. These will be used to qualify the electroless UBM process at PacTech for such small openings. Some wafers will be thinned to 285 μm like the sensors, others to 175 μm like for ROCs. Barrel pixel sensors have been produced at CIS with enlarged passivation openings of 30 μm diameter and optional Al-Si-Cu metallization. One ROC wafer from IBM is available. Together, these should be used for the production of the first live modules in 2013.

The VTT SnPb process has been evaluated using spare sensors and ROCs from the current ALICE-SPD [6] provided by the ALICE collaboration. The flip chip process, including reflow after bonding, was performed with the Femto bonder at FineTech. The process was validated by X-ray inspection and a destructive pull tests. In order to test the Femto flip chip bonder under extreme conditions, we prepared test structures with gold balls at KIT and bonded them with the Femto bonder, in fact, the gold balls require both larger bond force and higher temperature than SnPb and indium bumps. The flip chip process has been performed successfully.

Investment and schedule

PacTech is selling the SB^2 Jet machines (few hundred to industry so far) and offers the UBM deposition as a service, but not the bump bonding in large quantities. The purchase of an SB^2 Jet machine for solder ball deposition (370 kEUR) and a Femto flip chip bonder (350 kEUR) is therefore required.

The investment into bump bonding machines is large and dedicated to the CMS pixel upgrade. Several options (solder ball diameter, capillary cleaning, formic acid chamber, tray for testboard for known-good-die testing) are specific to the project. The investment should be recognized by CMS up to the agreed level for bump bonding cost.

The machines have to be operated in clean room conditions, which will be provided at DESY and KIT. Personnel will be trained to develop the necessary skills for reliable series production.

The purchase decision is imminent, as the delivery time of the machines is 5 months and the first demonstration module should be produced in 2013. In parallel, we pursue procedure optimization at PacTech, focusing on the test structures from VTT due in mid autumn, with smaller contact openings on the ROC-like structures. At the same time, we will also start the evaluation of the alternative/backup option based on SnPn and indium spheres at KIT and DESY.

Upon delivery, the machines have to be aligned and adjusted, using the same test structures. The first live demonstration modules will be produced using the recent sensors production at

CIS and an old IBM ROC wafer, hopefully in the first half of 2013. We will then be ready for a final decision whether bump bonding steps 1 and 2 will be performed in-house or just step 3 or all at an external company.

We expect to be ready for series production in early 2014, depending on the delivery of sensor and ROC wafers. UBM deposition, thinning, and dicing will be done at an outside company, probably PacTech. Bare module production and testing should then take place at DESY and KIT at a speed of two modules per day. We would thus need about one year to produce the modules needed for layer 4, including spares and reserve. Further modules for other layers or disks could be produced on these machine as well, extending the overall schedule. Additional personnel would have to be trained on the machines.

Summary

An alternative method for bump bonding of hybrid pixel detector modules, not involving photolithography, sputtering, or etching and therefore well suited for in-house production, is being investigated at DESY and KIT. The SB^2 Jet machine from PacTech is capable of depositing pre-formed solder balls by laser re-flow at a rate of 5 Hz, with re-working of missing spots. Flip chip bonding can be done on a machine like the Femto from FineTech. ROC- and sensor-like test structures have been produced at CIS and taken to PacTech and FineTech for solder ball placement and flip chip bonding. Ohmic measurements of solder ball contact chains showed good uniformity after an initial training session and a bump bond yield close to 99.9%. DESY and KIT propose to use the described in-house bump bonding process for the production of modules for the CMS BPIX layer 4. The necessary infrastructure and resources will be set up at DESY and KIT and the investments up to the agreed bump bonding costs should be recognized by CMS.

Mastering the solder ball placement and flip chip bonding technologies at two sites would allow us to produce the layer-4 modules within about one year. Additional modules could be produced on these machines if time allows and additional personnel is sent.

Afterwards, the machines would be available in CMS for R&D towards phase II upgrade tracker. The solder ball deposition introduces minimal thermal stress which is in general beneficial for silicon sensors and would allow to bump bond pre-irradiated samples, where the annealing process is an issue. For bump bonding of several square meters of hybrid pixel detectors the recent PacTech development of simultaneous wafer-scale solder ball placement using a form with grooves and holes for under-pressure pick-up looks attractive [5].

References

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