Wire Bonding
(For Microwave and Millimeter-Wave, on a low budget).

Luis Cupido - CT1DMK

Wire bonding a connection to a chip device is obviously as old the semiconductor industry itself however we don't usually deal with this problem as we use encapsulated devices all the time. The recent articles published on 47GHz /1/ and 76GHz /2/ that employ bare MMIC dice, shown us the usefulness of having that technology to freely play on the upper bands. It seems timely to make a presentation of the wire bonding technology that is mandatory for the application of such chip devices. In the following article an overview of the wire bonding techniques is presented. A possible application for the typical low-budget ham experiments is also analyzed and I also added my personal experience in this field with the intention to encourage others to refurbish or partially build a bonding machine. Having access to such an equipment is the way for serious experimenting on millimeter-wave with chip devices and that will certainly set an higher level of performance on your next high frequency design.

Brief History of wire bonding.

The first attempts to connect thin wires to germanium and silicon were made in the late fifties and the first report (to my knowledge) on wire-bonding was published in 1957 by the Bell Laboratories. In 1959 JW Beams made an article reporting the characterization of the metallic thin films strength, essential knowledge to the reliability of wire bonding. In 1971 Nowakowski and Villela proposed variations on the power tests on such technology. In 1972 the first general purpose bonding machines and automated tests allowed the optimization of the wire bond attachments parameters and by that time first discoveries of systematic failures to wire attachments and thin films were becoming to be know statistically. In 1973 Ravi & Philofski published a failure model for thin films while C.N.Adams developed a model for the wire failure near the ball bond. In the eighties millions of wire bonds were done routinely every day and several manufacturers appeared on the market with both big automatic machines and small manual machines covering die attachment, wire bonding and bonding strength tests. Many more reports were published in the nineties and some articles dedicated special emphasis to microwave and millimeter wave applications.

Basics.

In the wire-bonding process the wire, usually made of gold or aluminum, is used to establish the electrical connection from the semiconductor chip (in the microscopic world) to the external device leads (the macroscopic world). The wire size must be compatible with the semiconductor pad area and therefore quite thin (common wire diameters range from 15 to 25μm and thicker on power devices). There are basically two forms of wire bonding technique, the wedge bond and the ball bond.

In Ball-bonding the thin gold wire (Au) tip is melted with a small electrical spark forming metal ball at the end of the wire. Then the capillary from which the wire is fed presses the wire into the bonding pad on the chip (the actual attachment method is described later on in the article). The wire is now attached to the chip, the capillary lifts and moves to the connection pad (could be the chip assembly to move instead) where the capillary descends and attaches the wire to the metal connection pad. At this point while the capillary is down the wire is pulled back so it breaks close to the bonding area. After, the capillary is lifted and a few microns of wire is fed in, at this stage it is ready to ball forming and consequently to the next ball-bonding cycle. Actually a ball-bond starts with a ball type bonding but ends on a wedge like bonding, and is commonly referred as Ball-Wedge-bonding.

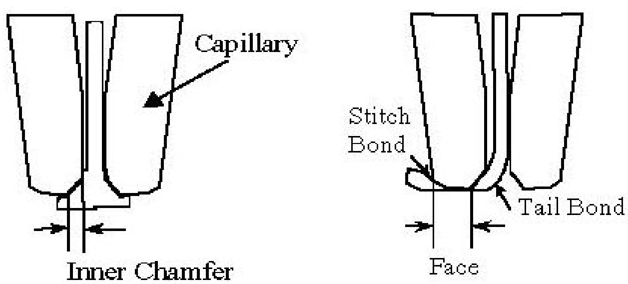

Fig. 1a – Ball bonding diagram.

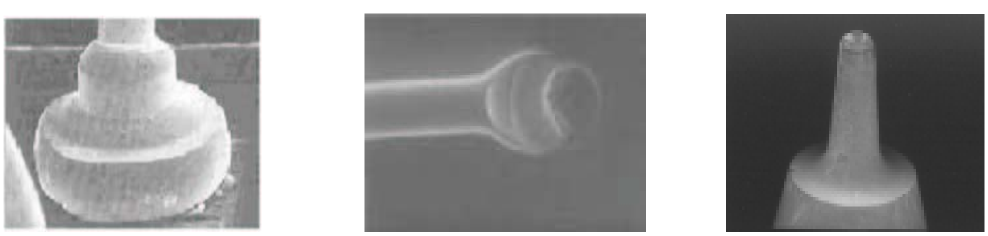

Fig. 1b – Ball first bonding, tail bonding and ball-bonding capillary tool.

In Wedge bonding the wire is pressed into the semiconductor pad horizontally and attaches in that position (the actual attachment method is described later on in the article), after the first bond the wedge tool tip is lifted and moves (or it could be the chip assembly that moves instead) to the connection pad position where, identically, the wire is attached horizontally, at this point the wire is pulled in order to break after the attachment bond area. The tool lifts and a few microns of wire are fed making it ready to the next wedge bond cycle.

As the wires are attached horizontally the bonding is directional representing a limitation to the wire connection freedom however it allows a smaller wire loop to perform the connection which is a relevant factor at millimeter-wave frequencies and also it can provide closer bonding that is relevant for smaller devices or with higher connection density. Also it allows quite easily stitch bonding that consists of bonding a single wire at several points without cutting the wire.

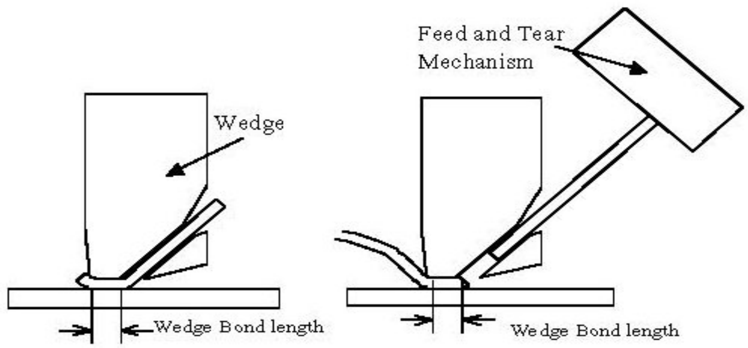

Fig. 2a – Wedge bonding diagram.

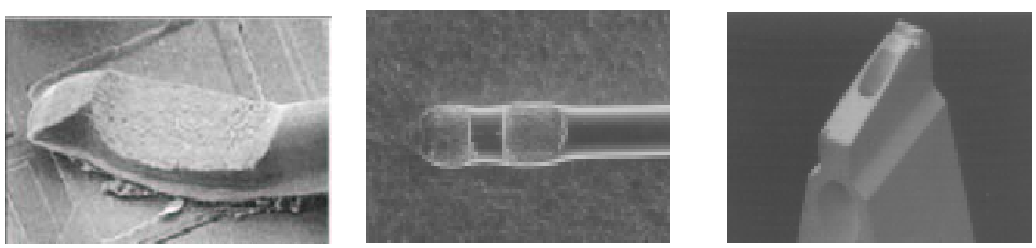

Fig. 2b – Wedge first bonding, last bonding and wedge tool.

Nowadays about 90% of the electronic chips are bonded using Ball-bonding technique while only 10% of the chips are Wedge-bonded however an increase of wedge bonding with thinner wires is expected as the devices are becoming smaller and with higher connection density.
For microwave and millimeter-wave applications most devices have a quite small bonding area, namely FET transistors that have about 40x50μm, the mm-wave MMICs have much larger pads however the signal connections are required to be as small as possible (and with impedances close to 50Ohm whenever possible) and in this respect wedge bonding has a clear advantage over ball bonding technique. To further improve the impedance of the signal connections sometimes gold ribbon is used instead of wire (providing the necessary wedge tool for the required ribbon size). It is quite common to see these MMICs using wedge bonding for the signal and ground connections while DC bias uses the ball bonding technique as the one we can see on figure 3.

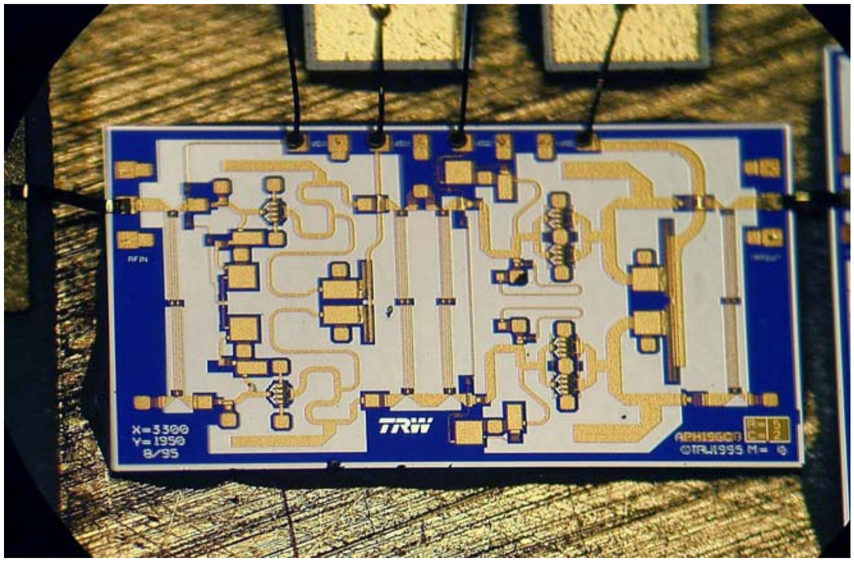

Fig. 3 – A TRW MMIC for 0.5W at 24GHz where ribbon bonding is used for the signal and ball bonding is used for the DC connections (magnified 40X , foto by CT1DMK)

The bonding attachment methods.

The wire bonding process requires the wire to become welded to the pad (both semiconductor or connection pad). To some extent there must be an intermetalic region with at least a few thousand atoms thickness (between the wire and the pad) that was actually melted in the process. The energy required to rise the temperature of this thin contact area can be supplied in the form of temperature, pressure, ultrasonic vibration or combinations of the above . The most common methods are listed below:

- *Thermocompression*

  Thermo-compression-bonding was first presented by bell Laboratories in 1957 and was extensively used until ultrasound technology appeared later in the sixties. The method consists of applying a relatively high force with the formed wire ball into the pre-heated chip or substrate. The operating temperature for this technique is about 250°C to 500°C and forces of 50 grams and higher are common. The wire material is gold and the semiconductor pad area could be either Gold or Aluminum.

- *Ultrasonic*

  Ultrasonic-bonding is a quite attractive method for both digital, analog and power semiconductors, but not on microwaves or millimeter waves. The method consists of applying a relatively smaller force pressing the wire to the chip at room temperature and applying vibrational energy in the form of ultrasounds. The wire material could be gold or aluminum (aluminum preferred) and the semiconductor pad area could also be either Gold or Aluminum. Despite the fact that this method can use aluminum and operates at room temperature the ultrasonic bonding is not the preferred method on semiconductor industry as reliability and bond strength tend not to be as good as with the thermosonic method described below.

- *Thermosonic*

  Thermo-sonic-bonding is the most common bonding method. It results from the combination of both previously described methods. It is performed at temperatures around 100°C to 200°C. Bonding is formed when the ultrasonic energy combines with the pressure on the wire-pad interface area. It is suitable for both ball-bonding and wedge-bonding. The wire material could be gold, aluminum or cooper (recently introduced) and the semiconductor pad area could also be either Gold or Aluminum. This method is in fact the most interesting for microwave and millimeter-wave applications.

Microwave and Millimeter-wave Devices

While for most digital and analog electronics the wire material is not critical, and often chosen according the bonding method, on high frequencies gold wire is the only used material, wires of 18µm or 25µm and sometimes in 50x10µm ribbons are the usual sizes used for high frequency chips. The recent GaAs FETs that operate at 40GHz and beyond place not only severe restrictions on the wire diameter but also on the wedge length and for this reason some tool manufacturers have special tools for microwave applications. For the vast majority of the devices the typical wedge tool for 18µm gold wire is sufficient for good results if bonded by an experienced operator (even if a special microwave tool version is recommended). The millimeter-wave MMICs are much less demanding as the bonding pads are considerably bigger however the 50Ohm nature of these devices require some care to be taken on the interconnection to the device. The chips itself are supposed to be attached to the ground by eutectic bonding such as conductive epoxy but in the case of bipolar transistors and schotky or varactor diodes in which the chip substrate is an active part of the connection (the collector or the anode) the indium based low temperature solder is probably a better method as it results in lower ohmic losses. For larger MMICs such as the one on figure 3 this is quite irrelevant as the contact surface is extremely big (compared with a FET or a Bipolar device).
Wire-bonding is a process that is usually associated with chip bonding to hard substrate, although recent publications shown good results while bonding to soft substrates if the right bonding parameters are employed /3/. So it becomes possible to bond from microwave and mm-wave devices into PTFE substrates such as RT5880 from rogers /4/ which give us a low cost alternative to the usual alumina substrates and enables easy construction of prototypes.

Practical bonding on a low budget.

The bonding machines were made available not only to cover the markets of mass production and medium production but also to the test and research laboratories. These smaller machines are usually manual or semiautomatic machines, to be operated by a single person, presumably a well trained operator. These are the ones that are interesting for the prototype builder or amateur microwave and millimeter-

wave experimenter however the price of such a machine new is prohibitive for non professional use.
Since the existence of such type of machines go as back as the sixties is would be expected that something should appear surplus, this is however only partially true.
The manual and semiautomatic bonding machines are composed of several parts and one must fully understand what is what before analyzing how good a price would be. Usually machines appear surplus without microscope and without bonding harm and without work-holder which makes them totally useless. Also we must be able to differentiate between wedge and ball bonding machines, also to determine if they are capable of termosonic bonding.

A fully functional machine in second hand could cost as low as 3000€, if we are lucky enough, but it is typical to find them advertised above 5000€. The termocompression bonders are somehow less expensive but I would recommend one capable of termosonic bonding. The most well know manufacturers of such small machines are WestBond, K&S (Kullicke and Soffa), Tempress, UTI and maybe others.

Another approach would be trying to find incomplete machine setups like missing the temperature controllers or the ultrasonic power generator, which are very simple devices to build. Or even with missing microscope which would not be too difficult to adapt another one. In this case I imagine that would be possible to have a functional bonding setup for less them 2500€ (my guess).
The closest to the build it yourself approach would be to buy surplus the bonding harm and chassis of a machine considered as scrap which should be not too expensive, however finding one may not be easy. In this case we would have to build all the electronics necessary to the operation of the machine, which is not a difficult task but it is quite an extensive endeavor. In this case we would use the latest digital electronics (or simply a PC control, why not) therefore resulting in a bonding setup that could be as good as a modern machine.

A bit of my personal experience.

I've decided to go along this route back in 1999 but at the time I had no idea of what I would be able to find surplus. Most of the units I was able to find fall in the '3000€ and above' category despite the fact they were surplus and sometimes looking very bad. Then I decided to search only for the guts of an old machine, mechanical guts I mean, as I was not worried about the control electronics that would be quite obsolete. With the help of friends that visit regularly electronic scrap dealers it was possible to find the rests of a Tempress wedge bonder but just the bonding harm and assembly was of any interest to me. So I had to build all the electronics to control this and also to develop the heated-work-holder and their XY movement controller etc. For that I used a microcontroller and a 'large' (320x200)LCD display and equipped the machine with all the possible bells and whistles that modern microcontrollers can provide, including automatic remote operation from a PC which is by the way a totally unnecessary luxury for the microwave and millimeter-wave experimenter. The results are so good that I may say that I'm as well equipped as I would be with an expensive K&S or HyBond machine, and considerably better than with a WestBond low-end machine. Hope this bit of my personal experience encourages others to repair recondition or even build a wedge bonding machine and expand the experimental horizons to the millimeter wave arena at a low cost.

Now some practical tips

Such an article wouldn't be complete without some experimental information for those that already started his first bonds or for the potential bonder that want to know what is expecting him.

Wire bonding tend to be a very frustrating activity specially for a beginner. Reliable bonding happens only when a number of conditions are met and there are a variety of parameters to be setup for which there are no substitute to many hours of experience.

A very useful tip is to have a log book where you take notes of the parameters you use each time you go for a bonding session. Noting down the type of tool tip, the forces, the US power, the times, the stage temperature etc can be a valuable information when things go wrong.

There is a significant difference on the bonding parameters, specially on the force and US power, for different bond wire diameters and materials. The 17µm gold wire requires considerably less pressure than the common 25µm wire.

Devices like FET and Bipolar transistors have usually quite small bonding pads and the 17µm wire is recommended, however most of the MMIC have pads large enough to accommodate 50µm ribbons at both input and output (which by the way is better than round wire to keep the impedances not too far from 50Ohm). If no ribbon and/or tool-tip is available placing two 25µm wires is also a very good solution. Bias connections are done with 25µm wire without trouble. Special attention to the high power MMIC that can sink more than 800mA at the last stage VDD connection a thicker wire or two
wires in parallel are recommended.

		17µm Au Wire	**25µm Au Wire**	**50µm Au Ribbon**	**25µm Al Wire**
Thermo-compression	Stage temp.	220° C	235° C	250° C	--
	Force	15-25 g	25-35 g	30-50 g	--
	Bond time	<0.3 s	<0.5 s	<1 s	--
Thermo-sonic	Stage temp.	125° C	150° C	150° C	≈20° C
	Force	5-10 g	10-18 g	20-30 g	10-15 g
	US Power	80-120 mW	150-250 mW	300-400 mW	100-200 mW
	Pulse duration	100-150 ms	200-500 ms	up to 1 s	200-500 ms

Table 1- Typical bonding parameters for wire bonding, indicative figures only as actual values to be used may depend also on other aspects not mentioned.

Special thanks to: Gary Leuterback AD6FP for his invaluable sharp eyesight locating an usefull bonding harm; To Max Muenich DJ3CR for the collection of chips and substrates that allowed me to perform tests and calibrations; to Will W0EOM for the many chips to play with; to Jim Vogler WA7CJO for the very usefull practical advices; Jac Smeets PA3KXH and Geert PA3CSG to trust me their Spectrum analyzer mixers for repair while I was doing my first steps; to Herman Hagn DC8CE

and Joe VE3VXO for the usefull hints and tips. Well, and thanks to all the others that did not laugh too loud when I announced that I was building such a machine.
For those interested I have a collection of photos of my bonder on my web pages http://w3ref.cfn.ist.utl.pt/cupido

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