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A STUDY IN SOLDER & FLUX

Modern electronics would not exist without solder. Every integrated circuit, passive component, wire, and connector is cleaned with an acid called *flux* and attached to printed circuit boards with a carefully engineered combination of metals called *solder.* This article discusses the physical and chemical nature of *solder* and *flux*.

EUTECTIC SOLDERS

You might have heard the term *eutectic* used to describe solder. But you might not know what it means -- which is a shame because eutectic describes a very interesting bit of physical chemistry.

Phase Changes of Pure Substances

As the temperature of a *pure* substance, such as water, increases, it will undergo phase transitions at specific temperatures and pressures. At sea-level, H20 changes phase from solid to liquid at 0 °C and from liquid to gas at 100 °C. The entire body of the substance absorbs any heat delivered to it during the transition and uses all of the thermal energy to change the phase of the material while maintaining a constant temperature. Elemental lead undergoes those same transitions at 327 °C & 1749 °C and elemental tin transitions at 232 °C and 2602 °C. But what happens if you don't have a pure substance but you are instead dealing with a carefully mixed *alloy*? That's when the really interesting things start to happen -- and it's not often taught in undergraduate electrical engineering coursework, so you've got a good excuse for not knowing it.

Phase Changes of Mixtures & Alloys

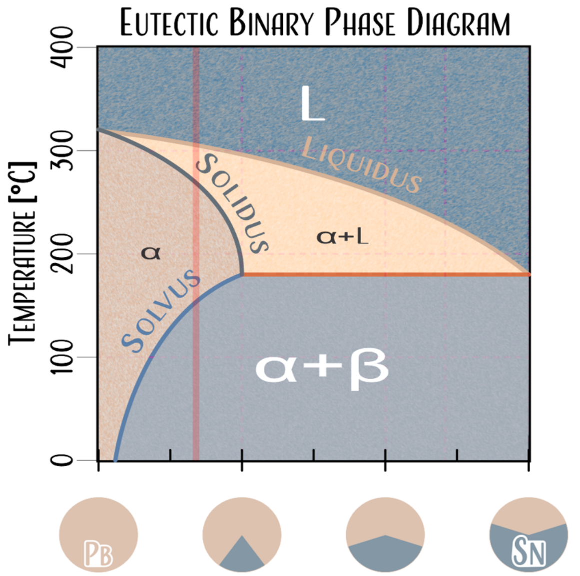
In *alloys*, the discrete transition temperatures that exist between the solid-phase α and liquid-phase L morph into transition temperature ranges as a new intermediate phase of matter appears that is part liquid and part solid α+L. The transition temperature range depends on the ratio of substances in the mixture and how thoroughly the substances are mixed.

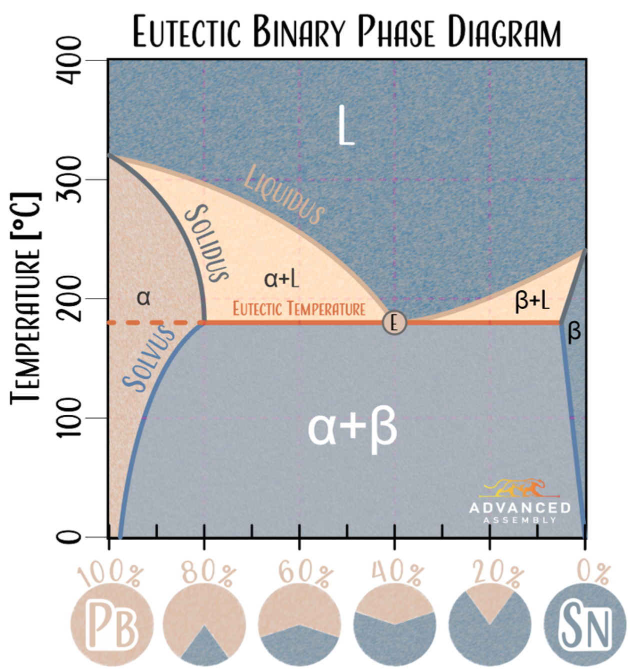
As a solid-phase alloy is heated, it begins to melt at a *solidus* temperature and is fully melted at the *liquidus* temperature. In between the solidus and liquidus temperatures, the mixture is a combination of solids and liquids α+L that can be thought of as paste. If you've ever seen dirty snow in the wintertime, you've likely seen that the intermediate phase appears as *slush* in a puddle.

This partial eutectic diagram shows the phases of lead-tin mixture based on mass ratio and temperature.

As you follow the red line vertically up the diagram, you'll see that it does not pass directly from solid α to liquid L, but crosses through a third phase α+L.

At a very particular ratio of materials, the *solidus* and *liquidus* temperatures meet at the *eutectic* point. The slush/paste phase completely disappears and the alloy transitions directly from the solid phase α+β to the liquid phase L in an isothermal process.





The graph shown to the left is a phase diagram for a lead-tin mixture. The vertical axis shows temperature and the horizontal axis shows the ratio of lead to tin -- with the percentage of lead, by weight, is shown. At 62% Sn, 38% Pb the solidus and liquidus temperatures meet at the *eutectic* point.

The *eutectic* (well-mixed) transition temperature is a discrete transition temperature that is lower than the transition temperature of either substance in pure form. This is important for microelectronics because it reduces the exposure of integrated circuits to high temperatures. But the lead/tin mixture is not the only one with a eutectic point. And non-eutectic solders are in wide use as well. The purpose of mixing metals is to create a solder composition that is, like all engineering, a compromise between material properties, performance, and cost. Having an assortment of solder to choose from allows a variety of benefits, the first of which is that it allows multiple reflow cycles during the PCB assembly process. An IC might be bound to a metal lead frame with a high transition temperature alloy and then the leadframe bound to an IC with a lower temperature alloy.

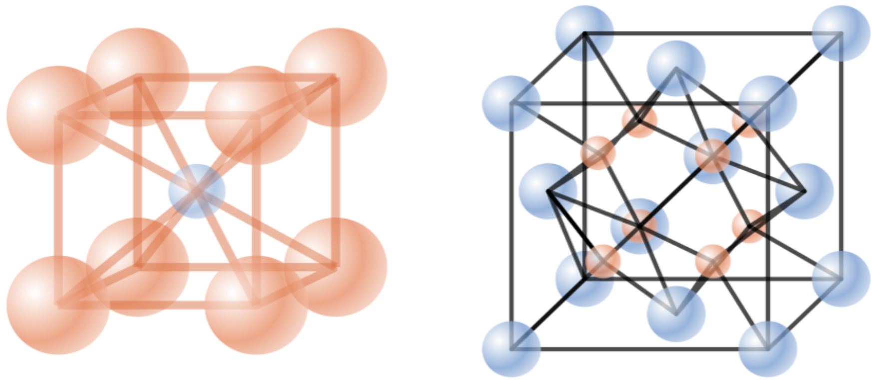
ALLOY [%]						SOLIDUS	LIQUIDUS	EUTECTIC
AG	AU	IN	PB	SB	SN	[°C]	[°C]	
3.5					96.5	221	221	●
25				10	65	233	233	●
	80				20	280	280	●
				5	95	235	240	
2.5		5	92.5			300	310	
			95		5	308	312	
2.5			92.5		5	287	296	

This table shows the metal composition of selected solders that are in use in the industry today. Some are eutectic solders while others are not.

It is generally thought that solder should transition between phases quickly. If a non-eutectic alloy is chosen, then the solids that begin to form during the liquidus transition will cause impurities to congeal in the still liquid parts of the mixture whereas a eutectic solder would freeze them in place, leaving the impurities dispersed throughout the solder. A concentration of impurities can cause a mechanical weakness in the solder that causes it to fail at a later date.

WHAT IS AN INTERMETALLIC?

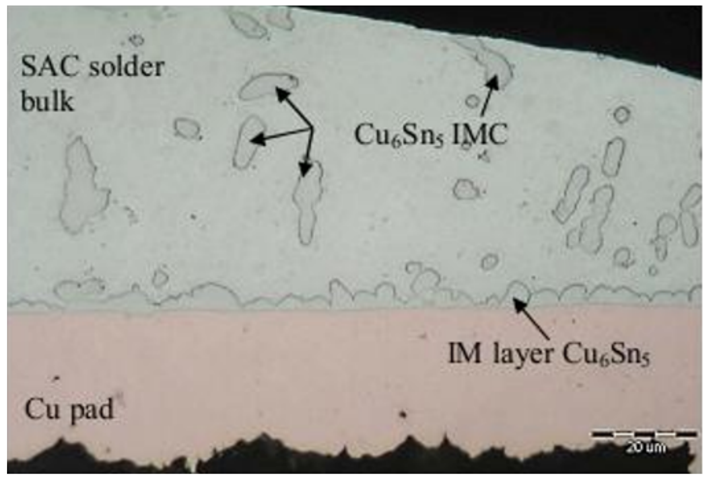
Metals are a class of elements with a particular chemical, mechanical, thermal, and electrical properties. They are of interest to electrical engineers due to their high thermal and electrical conductivities. When two or more metals combine in a crystalline arrangement with exact proportions of molecules, and have the same properties as elemental metals, it is referred to as an intermetallic compound. Examples include Cu_6Sn_5 and Cu_3Sn. Alloys are unordered mixtures of atoms whereas intermetallics are orderly crystalline arrangements.



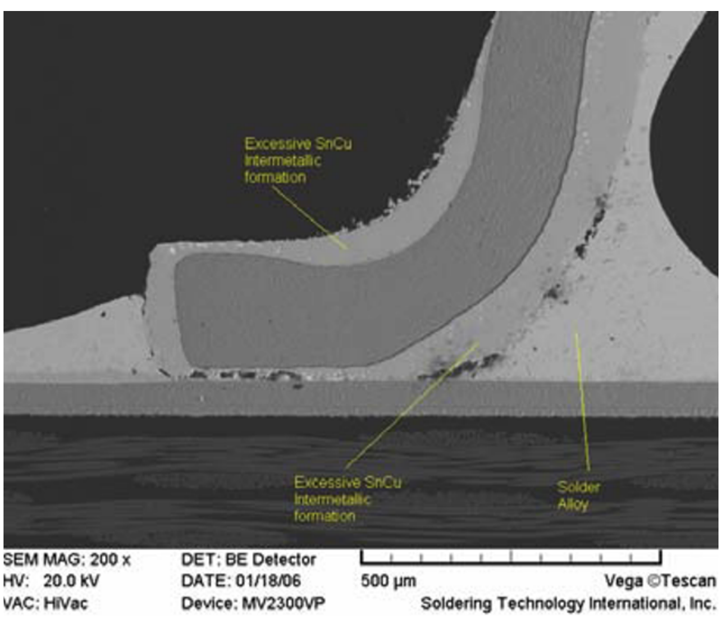
These crystalline structures show an orderly arrangement of atoms in a crystal. The images are “unit cells”, but in crystals the arrangement repeats in all directions until it reaches the edge of the crystal.

Intermetallic bond formation is crucial in solder joints. The copper on the surface of a circuit board will bond with the Tin in solder to form Cu6Sn5 layers on the metalized parts of a printed circuit board. Additional Cu6Sn5 or Cu3Sn intermetallic crystals will form in the body of the solder metal -- which can create structural weak points that cause failure over time. Solder is cooled in a fashion that allows some interfacial crystal growth, but hopefully not a great deal of growth.

At the microscopic level, the interfacial crystals appear as dendrites and give the molten solder an irregular surface and additional surface to adhere to.

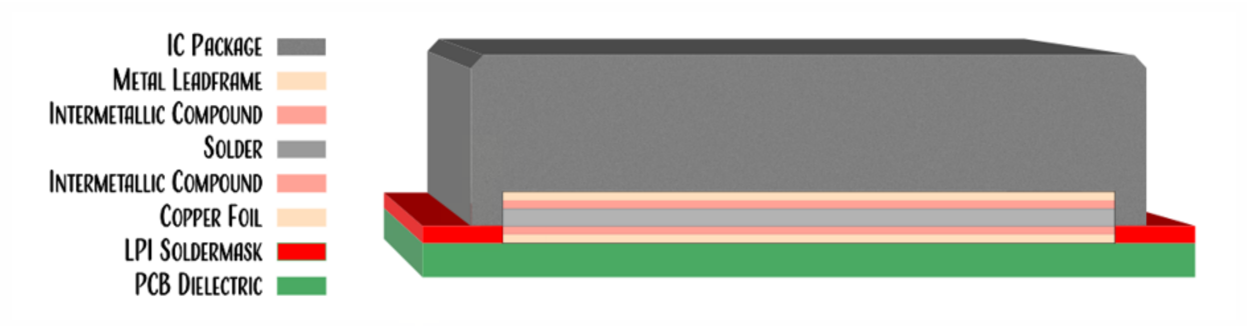


The cross-sectional microscopic image of solder on a copper pad above shows the formation of an intermetallic Cu6Sn5 layer that mechanically and electrically connects the pad to the solder. Image courtesy doktori.bme.hu



The cross-section of a J-lead connected to a printed circuit board to the left shows the consequences of excessive intermetallic growth. The underlying solder alloy does not successfully bond to the intermetallic formation. Image courtesy STI electronics

To form a proper bond, the metallic pad of an IC must form bonds with the solder, and the solder must then form bonds with the copper on the PCB pad. This cannot happen if there is any oxidation on the surface of either the part or the pad of the PCB. Flux is used to cleanse pads immediately before the solder covers the joint.



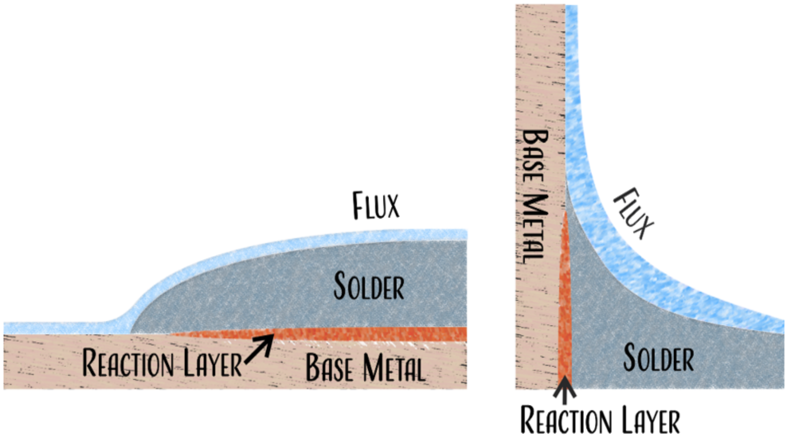
This cross-sectional illustration shows the various layers that could be expected on a properly bonded integrated circuit. The image is not-to-scale.

WHAT DOES FLUX DO?

Flux is used wherever solder is used to both clean the base materials and to decrease the surface tension of the solder. It is a collection of molecules that can strip oxygen atoms from the surface of a base material and provide an atmospherically impervious surface layer that prevents new oxygen molecules from bonding. In electronics, flux is mixed with the solder. In the case of plumbing, flux is applied immediately before solder metals are applied.

Base materials, such as copper, start to react with oxygen in the atmosphere the moment they from etching/electroplating tanks at the fabrication house. The oxygen binds to the surface copper molecules on the outer-sides of the PCB and prevents the solder molecules from bonding with the copper. Even if the oxide layer is sanded from the surface of the copper, it will reform almost immediately upon exposure to room air. A layer as thin as one or two molecules is sufficient to keep solder from properly bonding to copper.

The flux is designed to melt at a lower temperature than the solder so that it has time to react with the base metals. It spreads along the surface of a material and then floats atop the solder metal when the solder begins to spread.



The intermetallic compounds only form on clean copper. So flux (an acid) must be applied immediately before the solder. This is usually accomplished by mixing the flux into the solder paste. As the board is heated, the flux melts first, chemically cleans the copper and then floats on top of the solder due to its lower density than solder.

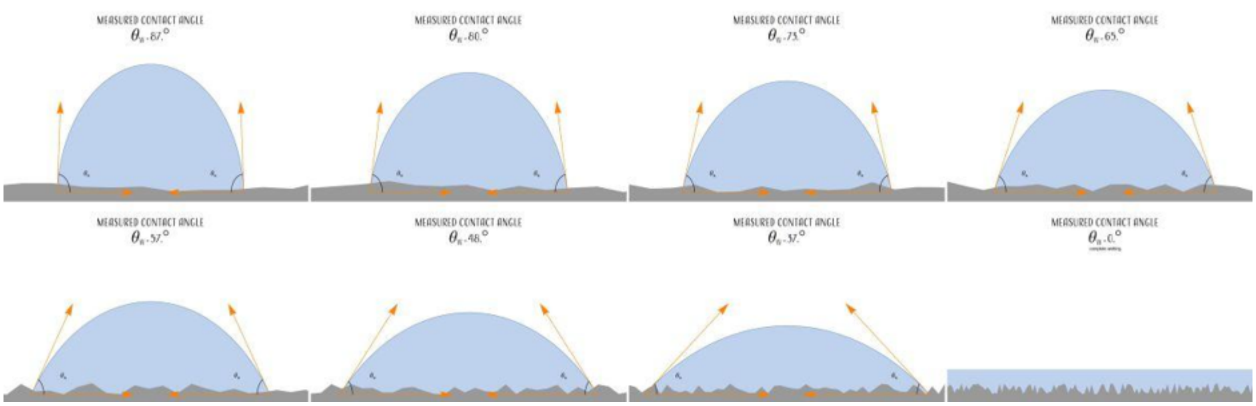
Flux also helps the solder to spread. Liquids are held together with *cohesive* forces and the molecules at boundaries are attracted to solid boundaries and other liquids with *adhesive* forces. The adhesive forces act over incredibly short distances of 10^{-9}-10^{-10} meters. Air molecules are spread out over a much greater distance than liquid flux molecules due to the phase difference. So when solder interacts with air, the adhesion is very low, so the solder tends to ball up. When solder interacts with flux, the adhesion is high, so the solder tends to spread out, or *wet*.

WETTING BEHAVIOR

To work properly, solder needs to spread and adhere to the metalized parts while in its liquid phase. The ability of solder to spread and stick is generally referred to as *wetting*.

The behavior of a liquid that is in contact with a solid surface is determined by the roughness of the surface as well as the magnitude of the cohesive and adhesive forces of the liquid at the interface. If the cohesive forces are very much greater than the adhesive forces, the liquid will "ball up" on the surface of the solid. This is the behavior of a raindrop on a freshly waxed car.

Intermolecular forces happen over the ~10^{-9} meter range. So only the liquid molecules that are at the interface interact. A rough surface has more surface area, and therefore more molecules available at the interface. This increases the cohesive force at the interface, and essentially pulls more of the liquid into contact with the solid atoms.



This compilation of images shows the effect of roughness on the wetting angle for an arbitrary liquid and surface of increasing roughness.

Good solders have a very low wetting angle approximately less than 30°.

SUMMARY

Modern electronics are held together with solder. Today's solders have highly engineered fluxes, melting temperatures, and wetting characteristics. If it wasn't for the tireless work of metallurgists and university researchers, we would have never survived the transition to RoHS products.

If you have questions about which solder to use in your next design, please contact Royal Circuit Solutions.