Diffusion Bonding of Gold

Giles Humpston and Sara J Baker

Marconi Materials Technology Ltd, Caswell, Towcester, Northamptonshire NN12 8EQ,UK

Gold has a low modulus and does not form an oxide skin when heated in the air. Added to this is its rapid self-diffusion characteristic and these three properties together make this metal suitable for joining gold to gold. This paper presents a summary of a practical diffusion-bonding method for making such joints.

Diffusion bonding is a well established method for permanently joining together two metal components. The process basically entails placing the two components in contact and using temperature and time to remove asperities from the interface by vacancy diffusion. The result is a fully dense joint line. Pressure is usually applied perpendicular to the bond region during the heat-treatment in order to force the mating surfaces into the closest possible contact and thereby shorten the process time. Obviously for the process to work it is essential that the metal surfaces are scrupulously clean and free of any oxide or other non-metallic films.

Among the many attractive features of gold are its low modulus, rapid self-diffusion and absence of an oxide skin, even when heated in air. These three characteristics render it a most suitable metal for effecting diffusion bonded joints. However a recent literature search failed to locate comprehensive data on suitable combinations of temperature, time and pressure to use. Accordingly a limited programme of experimental work was undertaken with this objective in mind.

Because diffusion bonding only involves closure of a joint gap, it is not necessary to employ substantial gold blocks as test pieces. Instead, substrates comprising ordinary borosilicate glass microscope slides were used. These are extremely flat, reasonably tough and will accept a gold coating over an active seed metal. Sputter deposition was chosen to metallize the glass slides because this method is a high energy process and thereby yields exceedingly well adhered metal layers of essentially theoretical density (1). In this instance the glass was sputter-coated with a thin layer of titanium (0.1µm) and platinum (0.1µm) overlaid with 3µm of gold. These metals were deposited in an argon atmosphere of 7mtorr. The titanium was deposited at 200W target power, 20W substrate power, giving a bias of approximately 95volts. The platinum and gold were both deposited at 100W target power. The resulting gold surface was extremely smooth with an Ra of 0.05µm.

Square coupons of varying dimensions were diced from the metallized glass slides and subjected to a range of applied temperatures and pressures. The process time was arbitrarily fixed at one hour. After diffusion bonding, a metal stud was attached to each side of the glass sandwich using a high strength epoxy adhesive. The assemblies were then subjected to uniaxial tension until failure at a cross head velocity of 3mm per minute.

The results are presented in Figure 1. The graph shows the expected inverse relationship between process temperature and pressure. The line denotes the boundary between good and failed bonds. In the interests of clarity only those results that straddle this line are included in Figure 1. As can be seen, the differentiation between a good and failed bond is quite abrupt and an increase in process temperature of only a few per cent is necessary to go from joints of negligible strength to ones where the epoxy adhesive fails at approximately 10-25MPa. The data are consistent with the limited process conditions reported in the literature (2, 3).

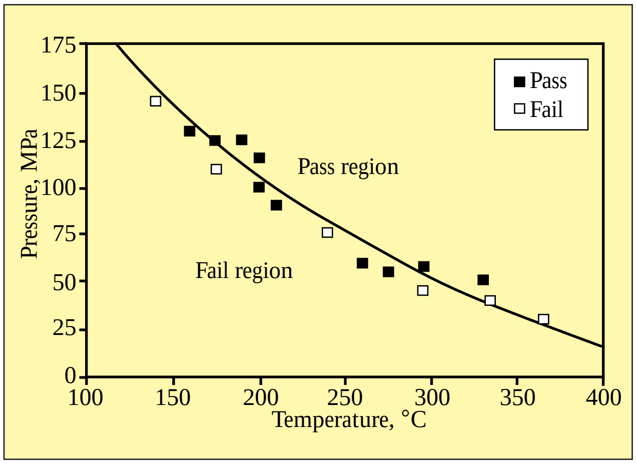

Figure 1 *Plot of process temperature against process pressure*

The line on the graph is the fitted curve of a simple natural logarithm equation. Because the correlation coefficient is high it is possible to predict that a successful bond will be achieved without pressure at temperatures above about 430°C. Certainly it is the author's experience that heat-treatment of a bundle of pure gold wires for one hour at 500°C resulted in a single rod and some hindsight into gold diffusion bonding!

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Low Resistance Gold Contacts for Gallium Nitride

Peter Boswell

Bricad Associates sarl, route de Genève, 7, CH-1291 Commugny, Switzerland

Gold is playing an important role in the development of reliable contacts with a very low contact resistance to gallium nitride.

Owing to its chemical inertness, gold is often the ideal contact material for semiconductor devices. However, new generations of semiconductors are continually entering mainstream applications, so device manufacturers must tackle fundamental challenges when continuing to use gold in novel types of contacts. The identification of a viable contact for gallium nitride demonstrates that gold's versatility often lies at the heart of modern contact systems based on sophisticated physical concepts. The system comprises a series of thin films deposited successively on the gallium nitride where the final, relatively thick (50 nm) film of gold provides the low-resistance connection to the exterior.

Gallium nitride has emerged mainly because the capacities of optical storage media used in domestic audio and video equipment and in computer storage devices increase remorselessly in the quest for higher performance. Solid-state lasers working in the blue to ultraviolet are necessary, and materials based on the II-VI and III-V elements race to become the dominant system. The ZnSe II-VI compound has received the most attention, highlighted by the announcement in 1994 of lasers capable of operating for over 100 hours. However, the GaN III-V compound with superior electronic and physical properties is the material of choice. For instance, the large energy difference for electrons sitting in the conduction and valence bands leads to a small leakage current and a large breakdown voltage, important properties for devices operating at high temperatures and at high frequencies. Unfortunately, producing defect-free GaN crystals is extremely difficult so there is no commercial source of GaN substrates for growing the layer structures used in solid-state lasers.

Meanwhile, GaN grown on sapphire substrates is now the material of choice for manufacturing the lasers' cousins, namely light emitting diodes (LEDs) that operate in the blue. So the installed production capacity for high-brightness GaN LEDs has leapt from almost zero a few years ago to over 10 million units per month worldwide. This has paved the way for using GaN LEDs in ubiquitous applications such as traffic lights. The potential for high-temperature and high-frequency applications and for short-wavelength detectors persists, with overall success ultimately depending on the future development of bulk materials and layer growth processes, and on substrate technologies in general.

LOW-RESISTANCE CONTACTS

In a semiconductor laser or LED, light is emitted when electrons, injected into the conduction band, fall into the lower energy valence band. So a high overall efficiency requires a low electrical resistance for the contact between current leads and the semiconductor. Developing stable and reliable contacts with a very low contact resistance to GaN is therefore a crucial issue.

If the difference between a semiconductor's valence and conduction band energies is not too large one can generally find a metal with a low enough work function which allows electrons to flow easily from the metal into the semiconductor. However, GaN's band gap energy of 3.42 electron volts is so large that a suitable metal with a small work function does not exist. Consequently, thermionic emission from the metal cannot be used as the basis for low-resistance contacts.

For an unreacted metal with a relatively large work function, the contact resistance is determined by the Schottky barrier height. Owing to the ionic nature of GaN, it was predicted by Forest and Moustakas in 1993 that the barrier height is given by the difference between the contact metal's work function and the electron affinity in the semiconductor. Confirmation that the work function determines the contact resistance of unreacted pure metal contacts on positively doped GaN came three years later (1).

However, the contact resistance for platinum, which has the largest work function from among the commonly available precious metals, remained 100-times too large for lasers. The sought-for reduction in the contact resistance (to the 10^{-4} ohm cm^2) level can possibly be achieved by reducing the barrier height - either by forming a thin intermediate semiconductor layer or by adjusting the semiconductor side of the contact (*eg*, by heavily doping the GaN surface layer).

ELECTRON TUNNELLING

If the energy of the GaN's conduction band near the metal-GaN interface is decreased sufficiently by doping (a process called 'band bending'), the tunnelling of carriers through a thin contact layer becomes the primary transport mechanism. Showing that an extremely low contact resistance can been achieved using this approach came quite by chance when Lin *et al* (2) used a thin Ti adhesion layer sandwiched between n-type GaN and an Al contact layer to obtain a well-bonded contact. The specific resistance they measured was only 8 x 10^{-6} ohm cm^2.

The Ti/Al contact layer lost its good conductivity during thermal annealing so a second composite layer had to be evaporated onto the Al layer after the thermal treatment. This represented a supplementary manufacturing step so Fan *et al* (3) investigated what could be achieved by tailoring both the process used to clean the GaN surface and the structure of the multilayer contact. A specific resistance of 8.9 x 10^{-8} ohm cm^2 was obtained by depositing a Ti/Al/Ni/Au (15nm/220nm/40nm/50nm) composite multilayer after reactive ion etching to clean the n-type GaN surface. The multilayer retained its low resistivity after thermal annealing, and the etching process and the formation of TiN at the interface introduced defects that reduced the barrier height for electron tunnelling.

Another approach for enhancing tunnelling relies on direct doping of the GaN surface layer. However, conventional doping techniques, based on the diffusion of alloyed ingredients from the deposited metal layer into the GaN to reduce the energy levels, do not work because reaction layers form during the high-temperature thermal treatments. Burm *et al* (4) have shown that a specific contact resistance of only 3.6 x 10^{-8} ohm cm^2 can be realized by implanting silicon in the n-type GaN before depositing a 3 nm Ti adhesion layer and a thick (300nm) Au contact layer. Thermal annealing to activate the dopants may cause complications and implantation represents an additional process step, so this particular approach may not be commercially viable.

The work confirms nonetheless the importance of recent developments in gold-based composite layers for low resistance contacts on highly doped GaN. As Fan *et al* conclude: "we confidently state that extremely low ohmic contact resistance is now possible on GaN which can pave the way for the exploitation of this material for high power/high efficiency amplifiers".

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