# Solid-state reaction-mediated low-temperature bonding of GaAs and InP wafers to Si substrates

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We report a low-temperature wafer bonding method for the realization of integration of GaAs- and InP-based optoelectronic devices with Si microelectronic devices. This method uses a Au-Ge eutectic alloy as the bonding material sandwiched between GaAs and Si wafers, and between InP and Si wafers. The bonding process was carried out at 280–300 °C by taking advantage of the low-temperature solid-state reactions occurring at GaAs/Au-Ge, InP/Au-Ge, and Si/Au-Ge interfaces. Both the simple mechanical test and standard thermal cycling test prove excellent structural integrity of the joined wafers. Structural analyses reveal only limited interfacial reactions as well as solid-phase epitaxial regrowth of GeSi alloys on the Si substrate.

The realization of integration of GaAs- and InP-based optoelectronic devices with Si microelectronic components relies upon the achievement of high quality epitaxial films of these materials on the Si substrates.[1–3] Extensive studies have been motivated on the heteroepitaxial growth of device-quality GaAs, InP, and related materials on Si substrates using molecular beam epitaxy (MBE), liquid phase epitaxy (LPE), and metalorganic chemical vapor deposition (MOCVD).[4–6] Due to the large lattice mismatches involved in these systems, an unacceptably high density of threading dislocation is generated during growth, which becomes the primary obstacle preventing their uses in device fabrication. By introducing strained-layer superlattices and various buffer layers, better epitaxial films have been achieved with improved minority-carrier lifetime and reduced threading dislocation density.

Recently, Lo *et al.*[7] demonstrated an alternative approach to optoelectronic integration for InP-based materials on GaAs substrates using the so-called bonding by atomic rearrangement (BAR) method. This technique requires high-temperature annealing (650 °C, 30 min) and a precise crystallographic alignment of the InP and GaAs materials in order to achieve epitaxy at the interface. To overcome these problems, Venkatasubramanian *et al.*[8] used Au as the bonding material between GaAs and Si, and developed a eutectic-metal bonding (EMB) method by making use of the low-temperature eutectics of Au-Si and Au-GaAs, but their bonding process involves liquid-phase reactions (430 °C, higher than the Au-Si eutectic point, 363 °C). It is conceivable that such reactions could result in very poor interface morphology such as thermal spiking. In this letter, we have extended our previous work of low-temperature solid-phase epitaxial (SPE) growth using Au as the transport medium and developed a low-temperature wafer bonding method, which utilizes a Au-Ge low-temperature eutectic alloy as the bonding material. The bonding is mediated by the solid-state reactions taking place at the GaAs/Au-Ge, InP/Au-Ge, and Si/Au-Ge interfaces as well as the SPE regrowth of GeSi alloys on the Si substrate. The selection of the Ge-containing alloy rather than pure Au is intended to suppress the dissolution of Si from the substrate into Au and to reduce the process temperature.

(100)-oriented GaAs, InP, and Si wafers were used in this study. They were cut into pieces of a size of (2×2) cm$^2$. After a standard degreasing procedure followed by chemically cleaning, the samples were immediately loaded into a thermal evaporator with a base pressure of about $2\times10^{-7}$ Torr. A commercial Au-Ge eutectic alloy was used as the adhesion material. About 800-Å-thick Au-Ge films were codeposited onto the cleaned GaAs, InP, and Si substrates. The Au-Ge alloy-coated samples were then stacked face-to-face, i.e., GaAs/Au-Ge/Si and InP/Au-Ge/Si, in intimate physical contact. The bonding process was carried out by annealing at 280–300 °C for 0.5 h in an alloying furnace. The strength and reliability of the joined structure were evaluated by a simple cleavage test as well as standard thermal cycling experiments. The joining interfaces were also examined by scanning electron microscopy (SEM) as well as transmission electron microscopy (TEM) equipped with x-ray microanalysis.

Figures 1(a) and 1(b) show cross-sectional scanning electron micrographs (SEM) for the joined samples of GaAs on Si and InP on Si, respectively. The cross-section samples were prepared by cleaving with a diamond scriber. The adhesion is seen to be fairly uniform across the entire region under inspection. Also, the original physical points of contact cannot be distinguished after the bonding, implying that atomic rearrangement occurred during annealing. Only limited reactions are observed at the interfaces. To obtain more detailed information about the bonding process, we further characterized the joined regions of the samples using transmission electron microscopy equipped with x-ray microanalysis. Since the preparation of TEM specimens involves both diamond-blade cutting and mechanical polishing down to about 30 $\mu$m, the preparation itself provides the initial stress test for the strength of the adhesion. Figures 2(a) and 2(b) are cross-sectional TEM micrographs corresponding to Figs. 1(a) and 1(b), respectively. In both cases, it is seen

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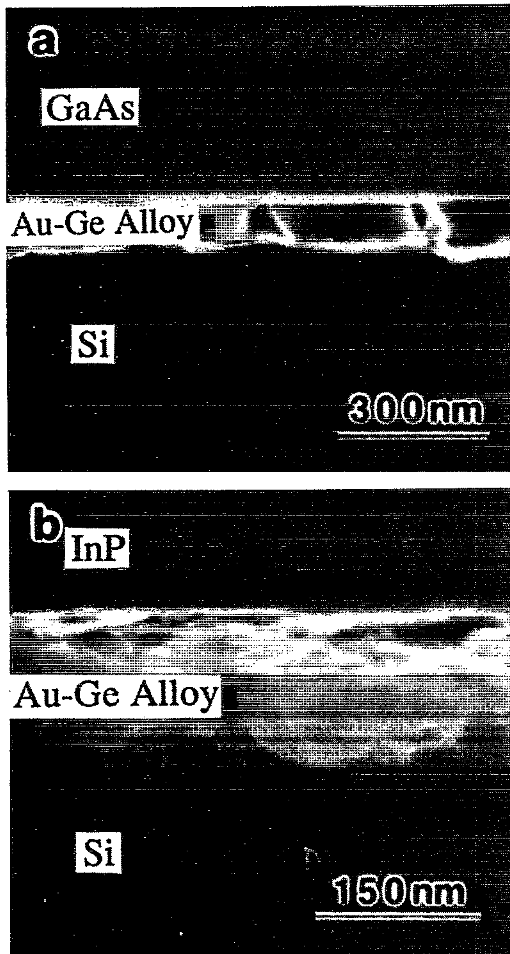


FIG. 1. Cross-sectional SEM micrographs of the joined wafers taken after the cleavage with a diamond scriber. (a) GaAs/Au-Ge/Si and (b) InP/Au-Ge/Si.

that the initially codeposited Au-Ge eutectic alloy separates into Au(Ge) and Ge regions during annealing. The phase separation process has destroyed the original physical contact surface by atomic rearrangement and thus realized the bonding. The interfaces are relatively smooth with no thermal spiking observed. It is deduced that the incorporation of Ge in the Au films largely suppresses the further dissolution of Si into the Au. This is expected in view of their simple eutectic phase diagrams where no stable compounds exist.[9] More interesting is that after phase separation, the Ge grows epitaxially onto the Si substrate. This is clearly shown in a high-resolution TEM micrograph (Fig. 3). X-ray microanalysis indicates that this epitaxially regrown region contains only a small amount of Si. They are believed to be initially dissolved in Au and then incorporated in the epitaxial film during regrowth.[10] The strain contrast is also seen in the image and is due to the large lattice mismatch between the epitaxially regrown region and the Si substrate (the interface is delineated by a set of arrows).

The reactions occurring at the interfaces between GaAs and Au-Ge, and between InP and Au-Ge were also examined. Similar to previous studies on Au-Ge based ohmic contacts to GaAs,[11,12] interfacial reactions are very limited at our an-

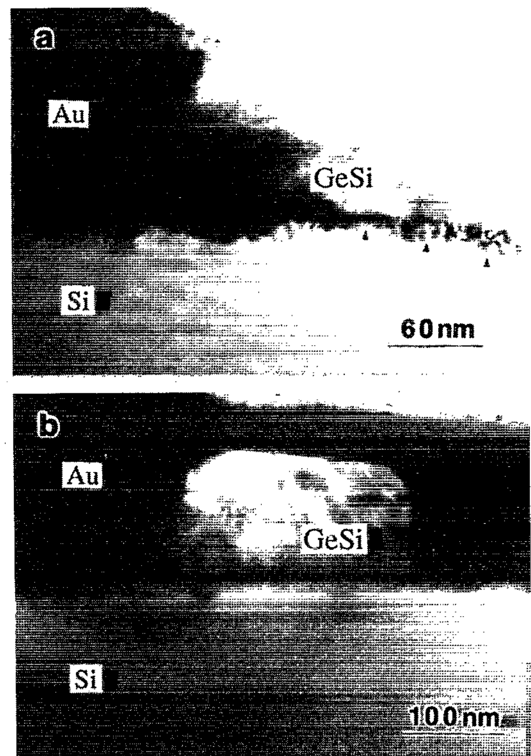


FIG. 2. Cross-sectional TEM micrographs of the joining interfaces after annealing (a) GaAs/Au-Ge/Si and (b) InP/Au-Ge/Si.

nealing temperatures. The major reaction products at this interface are Au-rich Au-Ga compounds, which were identified by TEM diffraction and x-ray microanalysis. At the InP/Au-Ge interface, In-rich In-Au compounds are found.

Based upon the microstructural characterizations, we suggest that the bonding is achieved by the low-temperature solid-state reactions occurring at these interfaces as well as the solid-phase epitaxial regrowth of Ge-rich SiGe alloy to the Si substrate via phase separation. The presence of Ge in the initial Au film not only suppresses the dissolution of Si into Au but also acts as a buffer layer between the joining

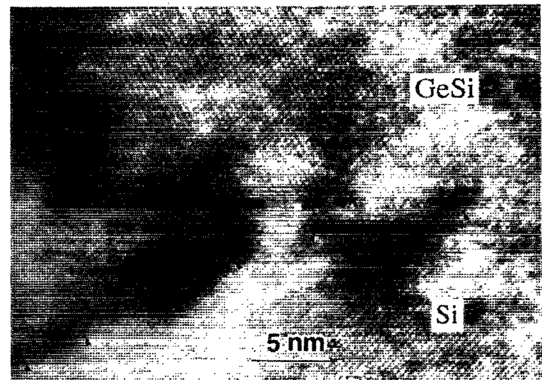


FIG. 3. High-resolution TEM micrograph showing solid-phase epitaxial regrowth of Ge-rich SiGe alloy to the Si substrate. The interface is indicated by a set of arrows. The contrast observed is due to the lattice misfit strain between the regrown SiGe and the Si substrate.


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materials through the heteroepitaxial regrowth owing to the close lattice constants and linear thermal expansion coefficients between Ge and GaAs or InP.

To further evaluate the strength and reliability of the joined wafers, we also performed a standard thermal cycling experiment with a temperature ramp from −50 to 150 °C for 15 cycles. The bonded wafers show very good structural integrity after the thermal cycling test even though there were further reactions at the GaAs/Au-Ge and InP/Au-Ge interfaces, as revealed by cross-sectional SEM observations. The residual elastic strain generated during thermal cycling is confined within the interface region and the Si substrate. This simple wafer bonding technique is governed by the low-temperature solid-state reactions and shows promise in designing new substrates for heteroepitaxial growth as well as in realizing the integration of GaAs- and InP-based optical devices with prefabricated Si electronic devices in hybrid circuit technology.

In summary, we have presented a low-temperature wafer bonding technique, which involves low-temperature solid-state reactions as well as solid-phase epitaxial regrowth, for the integration of GaAs- and InP-based optical devices with Si microelectronic components. The Au-Ge eutectic alloy as the bonding material not only suppresses the interfacial reactions but also enhances the bonding strength through heteroepitaxial growth. Both simple mechanical tests and thermal cycling experiments confirm excellent structural integrity of the joined wafers.

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