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A Survey of Ohmic Contacts to III-V Compound Semiconductors

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Abstract

A survey of ohmic contact materials and properties to GaAs, InP, GaN will be presented along with critical issues pertaining to each semiconductor material. Au-based alloys (e.g. GeAuNi for n-type GaAs) are the most commonly used contacts for GaAs and InP materials for both n- and p-type contacts due to the excellent contact resistivity, reliability, and usefulness over a wide range of doping levels. Research into new contacting schemes for these materials has focused on addressing limitations of the conventional Au-alloys in thermal stability, propensity for spiking, poor edge definition, and new approaches for a non-alloyed contact. The alternative contacts to GaAs and InP include alloys with higher temperature stability, contacts based on solid phase regrowth, and contacts that react with the substrate to form lower bandgap semiconductors alloys at the interface. A new area of contact studies is for the wide bandgap group III-Nitride materials. At present, low resistivity ohmic contact to p-type GaN has not been obtained primarily due to the large acceptor ionization energy and the resultant difficulty in achieving high free hole concentrations at room temperature. For n-type GaN, however, significant progress has been reported with reactive Ti-based metalization schemes or the use of graded InGaN layers. The present status of these approaches will be reviewed.

1. Introduction

The subject of ohmic contacts to compound semiconductors is a large topic with much relevant work to be covered. The purpose of this survey is to provide representative examples of the important approaches to ohmic contact formation on III-V compound semiconductor materials rather than to make any claim of an exhaustive treatment. Examples are chosen from three fairly different compound semiconductor materials, GaAs, InP, and GaN in order to give some idea of the similarities and differences in ohmic contact approaches to different III-V compound semiconductors.

2. Contacts to n-GaAs

A number of excellent reviews emphasizing different stages of ohmic contact development to GaAs are available [1-7], though the authors are not aware of any recent comprehensive reviews. For n-type GaAs there exists one contact which is a "gold" standard against whose electrical results all other contacts are judged and whose limitations provide motivation for all other contact work to n-type GaAs. That contact is the GeAuNi contact and its properties are reviewed below, followed by the different approaches to improving on its limitations.

2.1. GeAuNi Based Contacts

The GeAu contact is the earliest reported contact to n-type GaAs [8]. With a eutectic temperature of 361°C, this contact is prone to "balling up" as it melts during the contact alloy process and thus the morphology of the contact is poor and unsuitable for small area devices. Ni was added to the metalization to improve the wetability [9] and avoid the "balling up" process, but it was later deduced that Ni has other roles including reduction of the surface oxides, reacting with GaAs at low temperatures possibly forming electrically important NiAs phases, and possibly facilitating the incorporation of Ge dopant [10]. Good electrical contact resistivities better than 10^{-6} Ωcm^2 have been obtained with GeAuNi contacts. Incorporation of

Ge as a dopant in the GaAs region near the metal interface and formation of a small heterostructure barrier between epitaxial Ge and GaAs are the two most commonly cited structural explanations for the good electrical properties.

Though the GeAuNi contact has improved morphology over GeAu, it still suffers from a propensity to spiking, poor controllability, poor edge definition, and inadequate thermal stability for many applications. A major problem of the GeAuNi contact is the strong propensity to form AuGa, which has been observed in TEM at temperatures of 420°C and above [10] and is responsible for spiking and poor morphology. AuGa compound formation is limited essentially only by consumption of all of the Au or by interrupting the reaction by ending the heat treatment. Many methods have been touted for improving the morphology of the GeAuNi contacts [1] of which rapid thermal annealing and a properly optimized thickness of a Ni-first layer in a NiGeAuNi contact are the most promising. Rapid thermal annealing is one method for stopping the complex alloy reactions which include early reproducible termination of AuGa to limit the tendency for total consumption of the Au from the contact [11,12]. The use of Ni as the first deposited layer is said to improve uniformity of the contacts due to its ability to consume native oxides and the desirability of forming Ni_xGaAs compounds at temperatures below 400 °C [10], thus providing excellent electrical properties at low alloy temperatures and avoiding some of the undesirable Au-GaAs reactions.

2.2. *Improvements to Thermal Stability*

The conventional GeAuNi ohmic contact has demonstrated excellent reliability for GaAs MESFET and other commercial products. Nevertheless, temperature stability is an issue for high temperature device operation or post processing requirements after ohmic metal processing. Examples of these are certain CVD processes used for Al-compatible interconnects, some packaging applications, and high temperature electronics. In addition to better thermal stability, improvements to contact morphology are often attained by alternate approaches to the conventional GeAuNi contacts.

2.2.1 Contacts Based on Solid Phase Regrowth

The solid phase regrowth principle was originally developed to describe the alloy mechanism for the PdGe ohmic contact to n-type GaAs [13] but has been extended to describe other contacts with a similar behavior [7]. In the solid phase regrowth mechanism, one constituent of the ohmic metal, the Pd-like constituent, reacts with the GaAs at low temperatures to form intermediate phases which are not stable at higher temperatures. Thus, at temperatures well below 400°C Pd reacts with GaAs to form Pd_xGaAs compounds. A second constituent of the ohmic metal recipe forms a stable alloy with the first constituent at higher temperatures, e.g. the Ge with Pd in the PdGe contact. The process of reacting the Pd with Ge results in "regrowth" of the GaAs lattice to remove the Pd, which also affords the GaAs lattice an opportunity to incorporate defects or a dopant, such as the Ge in the GePd contact, which can improve the electrical properties. The advantages of these type of contact systems include excellent contact resistivity (in many cases) and excellent morphology of the contacts because of the overall limited reaction with GaAs and stable compounds formed by constituents of the contact itself. Other types of contacts developed to n-type GaAs with the solid phase regrowth principle include PdSi [14], PdIn [15], and PdInGe [16]. In the latter contacts In is utilized to create InGaAs layers during the GaAs regrowth process, which is also a surface bandgap lowering approach to be described in more detail in a later section.

2.2.2. Other Non-Au or Limited-Au Approaches

Because of the poor controllability of the GeAuNi alloy reaction regarding spiking and other non-uniform reactions, other non-Au contacts have been investigated both with and without addition of small amounts of Au. The non-Au contacts may sometimes fall under the category of solid phase regrowth, described in the previous section, but the key point of this section is that small amounts of Au can be useful for reacting with controllable amounts of Ga within the GaAs lattice. The simplest such contact is NiGe [17], which can be considered a solid phase regrowth reaction in the absence of Au since the Ni performs a similar role to Pd in the PdGe contact, both in the similarity of its low-temperature reactions with GaAs and the formation of a more stable phase with Ge. The NiGe contact resistance is about ten times worse than GeAuNi but is stable at alloy temperatures up to 600°C. Interestingly, addition of small amounts of Au (≈ 3 nm) improve the electrical properties such that the contact resistance is within a factor of two of GeAuNi and excellent thermal stability is obtained at 400°C [18]. Small amounts of Ag added to NiGe have a similar effect to Au [19]. Presumably the electrical improvement occurs by creating Ga vacancies which can increase the doping concentration by allowing Ge an abundance of Ga sites on which to incorporate as an n-type dopant.

AlGeNi [20] is another example of a non-Au contact which achieves 10^{-6} Ωcm^2 contact resistivity and is motivated by a higher AlGe eutectic temperature (424°C) than that of AuGe (361°C) to provide better thermal stability. More important than the higher eutectic temperature, stable phases such as Al_3Ni and NiGe compounds are formed within the contact structure after sintering at 500°C [21]. Another promising non-Au contact to n-type GaAs using Cu_3Ge exhibits a planar and abrupt interface and excellent contact resistivity of 6×10^{-7} Ωcm^2 to moderately-doped GaAs (1×10^{17} cm^{-3}) [22]. Ohmic contacts were observed with both excess Cu and excess Ge from a stoichiometric Cu_3Ge phase, suggesting that epitaxial Ge need not be a primary reason for the observed ohmic behavior. In addition, Ga was observed by SIMS in the $\varepsilon 1$-Cu_3Ge phase suggesting to the authors that Ga outdiffusion promotes Ge incorporation in GaAs as an n-type dopant.

2.3 Contacts Based on Heavily-Doped Surfaces

When the doping level increases above 10^{19} cm^{-3}, formation of non-alloyed ohmic contacts through a tunneling mechanism typically occurs and this will provide greater flexibility in the choice of metal for the contact. Common n-type dopants have a doping concentration limitation of $2\text{-}4 \times 10^{18}$ cm^{-3} in GaAs by ion implantation and most commonly used epitaxy methods, but there have been some novel methods to overcome this limitation. In one such example Sn segregation to the surface of an n^+ GaAs layer during MBE growth provided high surface concentration to allow a non-alloyed contact based using TiPtAu, Al, or TiW metals [23]. Non-alloyed ohmic contacts using $(NH_4)_2S$ surface passivation followed by thermal desorption in vacuum have been demonstrated, and it was suggested that the S incorporated below the surface as an n-type dopant, raising the surface doping level to 7×10^{18} cm^{-3} [24].

2.4 Refractory Metals and Contacts Based on Reducing the Surface Semiconductor Band Gap.

InAs with a bandgap of < 0.4 eV and a surface Fermi level that is pinned in the conduction band is an ideal surface layer for an n-type ohmic contact. Accordingly, InAs or InGaAs has often been used as an epitaxial surface contact layer for non-alloyed ohmic contacts, when the device allowed such a structure [25]. Surface InGaAs is also a motivating factor in ohmic metal structures containing In such as InW [26] and NiInW [27], to focus on two examples. In-containing contacts without the use of a refractory metal such as Ag-In [28], Au-In [29], Al-In [30], and Pt-In [31] have in the past typically produced contacts with high contact resistivities of about 10^{-5} Ωcm^2 or approximately one order of magnitude worse than GeAuNi contacts, which can generally be ascribed to uncontrollable, low temperature, liquid phase reactions with GaAs. The use of a refractory metal with In has greatly improved this situation by producing contacts with resistivities that are nearly identical to GeNiAu contacts for InW [26] and essentially identical by adding Si to the NiInW contact [32]. A number of other refractory In-containing contacts have been reported as well [1]. The refractory metal must be inert with the GaAs at higher temperatures than conventional ohmic contacts, since the InGaAs phases are formed and observed by TEM in the refractory contacts only after alloying above 600°C. Not surprisingly, the thermal stability of these contacts at 400°C is excellent. The role of the refractory metal is to cap a fairly thin In film to maximize the coverage of InGaAs phases at the GaAs interface. Films 3 nm thick were optimum for InW [26] with thinner films not producing enough InGaAs and thicker films resulting in poor thermal stability due to In-rich In(Ga,As) phases.

Other ohmic contacts using refractory metalizations, mainly W-containing materials, can be considered mainly as diffusion barriers separating another type of ohmic contact from a highly conductive metal such as Au. One such example is GePdWAu contact [33], where thin highly resistive GePd layers form the ohmic contact to GaAs by mechanisms described previously and the W acts as a diffusion barrier to separate a more conductive Au layer from the PdGe. Such contacts are touted as an implant mask for self-aligned ohmic contacts or for other high temperature processing needs.

2.5 Other Novel Contacts to n-type GaAs

Another new concept in ohmic contacts to GaAs involves the use of 5-50 Å of low temperature (LT) grown GaAs grown on top of conventional MBE grown GaAs:Si to generate non-alloyed ohmic contacts with contact resistivity as low as the mid 10^{-7} Ωcm^2 [34]. The LT-GaAs passivates the high space charge density layer on the surface of the MBE n-GaAs thereby permitting a tunneling contact, which normally requires heavily doping the GaAs to provide a thin enough depletion region to tunnel through. Finally, it is sometimes advantageous to be able to form an ohmic contact at lower than conventional temperatures and a PdGeAu contact with an alloy temperature of 175°C and contact resistivity of 10^{-6} Ωcm^2 has recently been reported [35, 36]. The high contact resistivity of a PdGe contact without Au is attributed to a highly resistive amorphous Ge layer that is formed at 175°C; in the presence of a top Au layer a low resistivity GeAu is formed instead of the amoouphous Ge. Other aspects of the solid phase reaction involving Pd, Ge, and GaAs are sufficient to form good ohmic behavior at 175°C.

Though much other work on ohmic contacts to n-type GaAs has been done, the examples presented here were chosen give a concise indication of the different types of ideas that have been pursued.

3. Contacts to p-type GaAs

For Au-based ohmic contacts to p-GaAs, many of the same considerations of GeAuNi n-type GaAs are also relevant including positive characteristics of good electrical results and negative attributes of Au spiking, poor morphology, temperature stability, and edge definition. AuZn [37], AuBe [38], and TiPtAu [39] are the most commonly utilized p-type contacts. Though the principles of Au-based and non-Au-based contacts to p-type GaAs are similar to those for n-type GaAs in most respects, several distinct differences exist. These include a lower barrier height for metal contacts to p-type GaAs making ohmic contact formation easier, a different choice of p-type metal for doping GaAs, a different metal for lowering surface bandgap - more often In for n-type GaAs and Sb for p-type GaAs - and relative ease in achieving p-type GaAs doping above 10^{19} cm^{-3} for the formation of non-alloyed ohmic contacts.

High p-type doping of GaAs is straightforward with epitaxy, diffusion, and ion implantation for a number of dopants including Be, C, Mg, and Zn. Non-alloyed ohmic contacts to these heavily doped GaAs surfaces are then chosen based on other contact properties required by the given application. Some examples include TiPt contact to GaAs:C grown by MOCVD to 5×10^{20} cm^{-3} [40], the highest reported doping level to GaAs, which allowed ohmic contacts with contact resistivity of 8×10^{-7} Ωcm^2. Non-alloyed W and WSi contacts to p^+ regions based on shallow Zn and Mg implants have also been reported [41], along with non-alloyed Au/Zn/Au contacts to Zn diffused GaAs [42], all with approximately 10^{-6} Ωcm^2 contact resistivity.

Many types of non-Au contacts with improved morphology and/or temperature stability have been reported for p-type GaAs. These include those based on solid phase regrowth using NiSi(Mg) and achieving contact resistivities < 10^{-6} Ωcm^2 [43], surface bandgap lowering using NiInW(Mg) with contact resistance of 0.8 Ω-mm [44], and contacts utilizing both solid phase regrowth and surface bandgap lowering using PdSb(Mn) with contact resistivity < 10^{-6} Ωcm^2 [45].

Much other work on ohmic contacts to p-type GaAs has been reported [1], essentially confirming the relative ease of obtaining good ohmic contact results to a material that can easily be doped to high enough levels to achieve tunneling ohmic contacts.

4. Contacts to InP

The conventional ohmic contact to n-type InP is GeAuNi and it shows many analogies to the related contact to GaAs. It shows good electrical contact properties with contact resistivities typically better that $1 \times 10^{-6}\ \Omega\mathrm{cm}^2$ but with many of the same shortcomings associated with a low eutectic temperature for GeAu: poor morphology, spiking, poor thermal stability, poor edge definition, etc. [46,47]. The GeAuNi contact to InP has been investigated by TEM and many analogous phases to those observed on GaAs were found [48]. Formation of ternary Ni-In-P phases were observed and their decomposition was correlated with the onset of ohmic behavior at 325°C. Higher temperatures result in Ni-P and Au-In compound formation, eventually resulting in higher contact resistivities.

Much of the ohmic contact research to InP has analogous counterparts in GaAs research. These include approaches to improve thermal stability of the contacts by using solid phase regrowth techniques such as PdGe [49], PtGe [50] operating with similar mechanisms described in the GaAs solid phase regrowth section and other non-Au contacts such as TiPt [51] for which good contact resistivities of $< 10^{-6}\ \Omega\mathrm{cm}^2$ have been achieved along with limited interfacial reactions with the InP. Other similar approaches to GaAs research include using a lower bandgap semiconductor such as InGaAs for the surface epitaxial layer [25], allowing non-alloyed contacts where the device design permits.

Other non-alloyed contacts have been investigated, including those made by depositing metal onto sputter etched n-InP surfaces [52]. In contrast to GaAs, sputter-etching of InP [52,53] has been found to create a damaged group III-rich surface with associated degenerate n-type doping, and in this procedure the metal deposition can be performed immediately following the initial sputter clean of the native oxide. Alloying has been used in combination with sputter etching prior to GeAuNi contacts formation and produces some of the best electrical results with contact resistivities < 1×10^{-7} Ωcm^2 [54].

Another sputter etching approach is based on the fact that InN produces an excellent ohmic contact to GaAs [55]. In this case the degenerately doped (10^{20} cm^{-3}) n-type InN is deposited by Metal Organic Molecular Beam Epitaxy (MOMBE) [56] and the high conductivity is due to the presence of native defects. These results suggest the formation of a nitrided surface layer on InP by low energy nitrogen ion bombardment can be an efficient technique for in-situ ohmic contact formation. Non-alloyed Ti/Pt/Au contacts deposited in-situ onto nitrogen ion bombarded n-type InP was demonstrated with contact resistivities as low as 3.4×10^{-6} Ωcm^2 using acceleration voltages of 100-300 V [57]. Electron diffraction patterns matching those of polycrystalline InN were identified in this degenerately doped surface layer.

Recently, n-type doping in InP has been increased up to 10^{20} cm^{-3} by using Te as dopant grown by MOMBE with a novel metal organic source, di-isopropyl tellurium. A contact resistivity of 1.0×10^{-6} Ω-cm^2, was obtained with non-alloyed sputtered WSi ohmic metal contacts and the contact metalization was stable up to 700°C [58]. Contacts based on reducing the surface semiconductor bandgap using sputtered W-Sb to n-type InP with contact resistivity in the low 10^{-6} range have also been reported [59].

Fabrication of p-type ohmic contacts to InP is difficult because of a large barrier height of most metals to p-InP as well as the large hole effective mass which limits hole transport properties relative to n-InP. The conventional p-type ohmic contact to InP is AuZn based or AuBe based [60,61] although other p-type dopants have also been used with Au. Contact resistivity is dependent on the substrate doping and a typical value of 3.7×10^{-5} Ωcm^2 is achieved for doping level of 10^{18} cm^{-3} [60]. Alternative p-type contacts with better morphology have been reported using several approaches. One such contact involves the use of Pd/Zn/Pd/Au [62]. Pd_2InP forms at low temperatures followed by PdZn at 250°C. Decomposition of PdZn to form PdP_2 at 400-425°C is thought to free up Zn to dope the InP. Minimum contact resistance of 7×10^{-5} Ω-cm^2 occurs when of Pd_2InP phases are adjacent to the InP followed by a thin layer of PdP_2. Another type of contact with improved morphology is based on the solid phase regrowth principle using Pd/Zn/Pd/Ge with 50-150 Å of Zn sandwiched between layers of Pd [63,64]. Pd reacts first with InP and at higher temperatures with Ge in a similar way to that described on GaAs; as the InP undergoes regrowth by Pd reacting with the Ge, the Zn is able to dope the InP and a contact with low 10^{-4} to low 10^{-5} Ωcm^2 resistivity was obtained [63,64]. Similar contacts using either Mn or Mg in place of Zn were not ohmic [63], but a Pd/Zn/Pd contact without the use of Ge was fabricated with contact resistivity in the mid 10^{-5} Ω-cm^2 [60]. Finally, contacts based on reducing the surface semiconductor bandgap using W-In-Sb to p-type InP with contact resistivity in the low 10^{-5} range were also reported [59].

5. Contacts to GaN

The most widely used Ohmic contact to n-type GaN is based on TiAl. While initial work reported the use of a single Al-layer [65], its was later shown that the addition of a Ti-layer significantly improved the contact resistance [66]. The improvement with Ti has been attributed to either the formation a degenerate n^+-surface layer resulting from N-gettering (and N-vacancy donor formation) to a TiN layer or to the Ti acting to reduce a surface oxide [67,68]. In either case, the Al overlayer is superior to a Au overlayer which suggests that a Ti/Al alloy may play a role in the contact formation [66,68].

Enhancements on the Ti/Al contact scheme have focused on modifying the GaN surface prior to metalization. One such approach is to expose the GaN surface to a plasma that will remove a higher fraction of N than Ga at the surface, creating N-vacancies (which act as donors to form an n^+-layer), and then promote tunneling currents [69]. In a similar way, a degenerate surface layer can be formed by a high temperature annealing step where N is preferentially lost from the surface [70,71].

An alternative approach is to use external means, such as ion implantation or diffusion, to create the high surface doping and thereby reduce the contact resistance. This has been done by implanting a high dose of Si-ions in the near surface of GaN, annealing the sample at 1100 °C, and evaporating a Ti/Au contact layer [72]. This resulted in a specific contact resistance of $3.6\text{x}10^{-8}$ Ωcm^2 for the implanted sample compared to $9.2\text{x}10^{-5}$ Ωcm^2 for an unimplanted, annealed sample.

Still another approach to low resistance n-type contacts to GaN is to employ highly doped, lower bandgap epitaxial layers as is done with InGaAs layers on GaAs. The analogy in the nitride material system is the use of an n^+- InGaN layer, which can be grown degenerately n-type due to intrinsic defects, to form low resistance contacts. This approach was used to achieve specific contact resistance of $1.2\text{x}10^{-7}$ Ωcm^2 between Ti/Pt/Au metalization and a degenerate n-type InN layer grown on GaAs [55,56]. In addition, thermally stable ohmic contacts based on refractory W metalization on InGaN and InAlN layers have been reported [73]. A related approach is the use of a short-period super lattice (SLS) to grade the potential barrier between the metal and GaN. Lin, et al., did this with a InN/GaN SLS and Ti/Al metalization to achieve a specific contact resistance of $6\text{x}10^{-5}$ Ωcm^2 without any post-deposition annealing [74].

The success with ohmic contacts to p-type GaN is much more limited than that discussed for n-type material. The primary limitation in p-type GaN is the large acceptor ionization energies (~170 meV or higher) that limits the number of ionized free holes at room temperature to less than 1% of the substitutional acceptors in the lattice. This in turn causes high sheet resistance (low free carrier concentration) in the p-type layer and limits the tunneling current typically responsible for low resistance contacts. To date, the best contact metalization for p-type GaN is based on a Ni/Au bilayer. Ni is selected since it has a relatively large work function (~5.2 eV) that should facility p-type contact formation based on the ideal case where the metal work function is larger than the semiconductor work function for ohmic contact to a p-type semiconductor [75]. Unfortunately, the work function of p-type GaN is ~7 eV so this situation can not be satisfied with any metal contact. This means that the current flow will be limited by a potential barrier at the metal/semiconductor interface since significant tunneling currents are difficult to achieve. This approach has achieved a contact resistance on-the-order-of 10^{-3} Ωcm^2 that is too high to allow low threshold laser fabrication.

Areas for future work for p-type ohmic contacts to GaN include development of p-type doping of InGaN to allow lower bandgap contacting layers and the exploration of acceptor species with smaller ionization energies.

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