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ULTRA-LOW RESISTANCE CONTACTS TO GaAs/AlGaAs QUANTIZED HALL RESISTORS

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Contacts to quantized Hall resistors (QHRs) must meet demanding specifications for contact resistance, reliability, ruggedness, and resistance to degradation. A study of contact materials showed that contacts composed primarily of Indium meet all of these specifications, but experience has shown that contacts of sufficient quality are hard to make reproducibly. The principal factors influencing contact quality are the concentration of electrically active defects in the contact region, and the uniformity of the metal-semiconductor interface. The former can be minimized by the use of high purity materials and careful cleaning. The work reported in this paper has resulted in the development of a technique for reliably producing contacts with high interfacial uniformity and high quality.

INTRODUCTION

Since the adoption in January 1990 of the quantized Hall resistance as a practical representation of the unit of resistance by the Consultative Committee on Electricity (CCE) [1], national standards laboratories around the world have begun to use quantized Hall resistors (QHRs) to provide the basic unit for their resistance calibration services. Most of the devices in use at national standards laboratories are prepared from GaAs/AlGaAs heterostructures because of the relatively ready availability of high quality material. While these devices are similar in structure to high electron mobility transistors (HEMTs) -- they use essentially the same type of heterostructure, and the contacts are similar to the source and drain contacts on HEMTs -- they must meet far more stringent criteria [2].

In addition to restrictions on the design of the heterostructure, such as the density of electrons in the two dimensional electron gas, the uniformity of the donor densities and thicknesses of the layers in the heterostructure, and the tolerances on the residual conductivity of the donor and buffer layers, standards-quality quantized Hall resistors must have absolute contact resistances of the order of milliohms or less, be independent of current up to currents of at least 0.1 mA, and furthermore, must achieve these specifications at temperatures below 1.2 K in magnetic fields between 5 T and 14 T. Since vibration of wires used to connect the device to the cryogenic probe in which it is mounted during use can have a significant effect on measurements, which typically have resolutions and relative uncertainties approaching 10^{-9}, it is often necessary to use 50 μm, 100 μm, or larger diameter wires for this purpose. Since bonding such large diameter wires to the fragile GaAs device is nearly impossible, and since soldering such wires to alloyed AuGe/Ni contacts causes long-term degradation of the contact quality, materials commonly used to make ohmic contacts to HEMTs do not produce optimum performance when used with QHRs. Furthermore, QHRs are repeatedly cooled to temperatures less than 1.2 K and warmed to room temperature, often encountering conditions of very high humidity which can cause corrosion and associated degradation of the contact quality. This degradation is particularly noticeable with alloyed AuGe/Ni contacts to unpassivated QHRs [3].

The object of the present study has been to identify materials that can be used to make contacts meeting these demanding specifications and to develop techniques for producing such contacts with very high yield. Degradation of AuGe/Ni (commonly used to make source and drain contacts to HEMTs) and tin contacts to QHRs under normal usage led to the search for other contact materials. Ohmic contacts, the principal constituent of which is indium, were found to meet the requirements of standards-quality QHRs: large diameter wires are easily attached without damaging them, they can be prepared with the requisite low contact resistances, and they are the most resistant to degradation of any of the materials tested. Indium-based contacts, however, are very difficult to prepare with high yield. The identification of the factors that influence the contact quality has been the subject of much study. This paper reports a procedure resulting from this work, which produces contacts with high interfacial quality.

EXPERIMENTAL

The heterostructure used in this work was grown on a (100) oriented undoped single crystal GaAs substrate. Molecular Beam Epitaxy was used to grow on this substrate a 1 μm thick undoped GaAs buffer layer, a 12 nm thick undoped $Al_{0.28}Ga_{0.72}As$ spacer layer, a 35 nm thick $Al_{0.28}Ga_{0.72}As$ donor layer containing $2x10^{24}/m^3$ silicon atoms, and finally a 10 nm thick GaAs cap layer, also containing $2x10^{24}/m^3$ silicon atoms. In order to facilitate attachment of large diameter wires to the contacts, beads of indium and indium-tin alloys with diameter between 0.1 mm and 0.5 mm were placed on the top of the heterostructure and heated. The indium and indium-tin alloys were prepared from 99.99% pure indium and tin wires with diameter 0.125 mm.

Quantized Hall resistors are fabricated by applying a Hall bar pattern (0.4 mm wide by 5 mm long channel, with potential probes placed symmetrically on opposite sides of the bar, separated by 1 mm along the length of the bar) using photolithography and etching the heterostructure in a solution of 1 part concentrated sulfuric acid, 8 parts 30% hydrogen peroxide and 10 parts water.

The photoresist is then removed by rinsing with acetone, and the device is cleaned by boiling, with moderate ultrasonic agitation for 5 minutes each in semiconductor grade trichloroethylene, and acetone. To remove gallium oxides on the surface, the sample is heated and ultrasonically agitated for 5 min in a solution containing 1 part 37% HCl to 10 parts semiconductor grade methanol, and then boiled. Upon boiling, the solution is decanted, the indium beads are placed upon the surface of the heterostructure, and the device is immediately placed in the furnace chamber. The indium and indium-tin beads were cleaned in a very similar manner, including boiling in the HCl-methanol solution.

The use of a solution of HCl in methanol was chosen as the final cleaning step for a number of reasons: the HCl dissolves both indium, tin, and gallium oxides, leaving the surfaces of these materials quite clean; and unlike aqueous solutions of HCl, when boiling solutions of HCl in methanol are decanted, they evaporate quickly from the wire and the sample, leaving them quite clean and dry. In addition, the surfaces are coated with a thin layer of adsorbed chlorine which protects them from further oxidation for a short period (of as much as 15 minutes) during which time the sample can be placed in the alloying furnace. Evidence for this adsorbed coating is found in a very thin yellow coating of indium chloride that forms upon the indium beads when they are heated, even in an evacuated chamber.

In initial experiments, the heterostructure with indium beads was placed in a chamber, which was purged with hydrogen gas at atmospheric pressure, and then heated. The thin indium chloride layer that forms on the indium beads, however, is quite volatile, subliming quickly even at temperatures below it's melting point (of about 225 °C). When it has evaporated, even small amounts of water vapor in the hydrogen gas can result in the formation of a tenacious native oxide on the indium which prevents the metal from making uniform contact with the substrate unless a suitable flux is used. The wetting action of chloride containing fluxes such as InCl formed by reaction of HCl vapor with the indium in-situ during heating, however, is highly temperature dependent: at low temperatures it has no effect; but at a critical temperature between 220 and 230 °C (very close to the melting temperature of indium monochloride), it causes the indium to so suddenly wet the surface that many small bubbles of ambient gas are entrained at the metal-GaAs interface.

When making contact to bulk GaAs, these bubbles do not have significant effect, for the solubility of GaAs in indium and indium-tin alloys is very high, the GaAs is rapidly dissolved in a lateral direction undercutting the bubbles and quickly resulting in a fairly uniform metal-semiconductor interface. In the case of the heterostructures used to make QHR devices, however, the GaAs cap layer is very thin, and the underlying AlGaAs layer is not very soluble in molten indium or indium-tin alloys. As a consequence, the thin GaAs cap layer is rapidly dissolved in places where the indium does wet the cap layer, but the indium dissolves the AlGaAs slowly and does not appreciably undercut the semiconductor underneath the bubbles. The indium then penetrates the AlGaAs layer in localized "spikes", which result in a highly nonuniform metal-semiconductor interface which produces unacceptably high resistance contacts under the conditions of the Quantum Hall Effect [4].

In order to avoid the formation of bubbles, it is necessary to minimize the amounts of water vapor and flux present in the system. This was accomplished by placing the cleaned device with indium beads on a thin metal foil susceptor inside a quartz chamber, which was then rapidly evacuated to a pressure of less than 30 mTorr. The susceptor was heated inductively at a rate of about 200 °C/min to a temperature of 500 °C for 5 min. The low pressure ensures that there is little oxygen or water vapor present in the chamber and the rapid rate of heating permits the indium chloride flux to melt, reducing the surface tension of the indium and permitting the indium to wet the GaAs before the flux evaporates. Furthermore, the very limited amount of adsorbed chlorine greatly reduces the amount of indium chloride present when the indium wets the heterostructure. This, together with the absence of ambient gas and water vapor in the chamber, nearly eliminates the formation of bubbles at the metal-semiconductor interface.

RESULTS AND DISCUSSION

The principal factors influencing the quality of the contact are the concentration of impurities and electrically active defects in the contact region, and the quality and uniformity of the metal-semiconductor interface. The use of high purity indium and careful cleaning minimize the concentration of impurities in the contact region. The effectiveness of the alloying procedure reported above in producing a uniform interface was determined by etching away the indium beads after alloying. The procedure was found to greatly increase the uniformity of the metal-semiconductor interface: in the best cases, the interface was mirror smooth, and in the worst case, only one or two small bubbles were present in an otherwise perfectly uniform interface.

The resistance of these contacts is measured under the conditions of the quantum Hall effect, by utilizing a unique property exhibited by quantized Hall resistors: when the devices are cooled to temperatures less than 1.2 K, and the magnetic flux density is set to a value in the middle of a "plateau" in Hall voltage (the "plateau" being a range of magnetic flux density over which the Hall voltage is independent of magnetic field strength, and assumes a value equal to IR_K/i where I is the current through the device, $R_K = 25812.807\ \Omega$ and i is an integer) the spreading resistance between pairs of potential probes on the same side of the device vanishes. Three terminal resistance measurements are made by injecting current into contact A and withdrawing it through another contact C, and measuring the voltage between contact A and an intermediate contact B on the same side of the device as contact A [3]. The best contacts made using this technique have absolute contact resistances less than 1 mΩ with areas as small as 100 μm square, giving specific contact resistances as low as $10^{-7}\ \Omega\text{cm}^2$, and are mechanically rugged, and resistant to degradation by corrosion in humid atmospheres.

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