Measurements of Al content in Ga$_{1-x}$Al$_x$As using nuclear resonances

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The resonant nuclear reactions, $^{27}$Al($p,\alpha$) and $^{27}$Al($p,\gamma$), were used to determine the Al distribution in GaAlAs samples. By varying the incident proton energy, the Al concentrations at different depths were measured. The results agree with concentrations measured with other methods. The present techniques serve as nondestructive, accurate methods of profiling Al in various materials.

Substantial researches have been focused on high-speed electronic devices using GaAs/GaAlAs heterostructures. Knowing the Al concentration and its distribution in the heterostructure is extremely important in the device fabrication. Although several methods such as secondary ion mass spectroscopy (SIMS), Auger spectroscopy, scanning electron microscopy (SEM), or photoluminescence can be used to determine the Al concentration or the thicknesses of the GaAlAs layer, there is no satisfactory analytical method that can measure the Al profile in a device structure nondestructively. In this paper, we study the feasibility of measuring Al profiles in GaAlAs using nuclear resonances.

The use of various nuclear resonances to determine concentration versus depth (concentration profiling) has been described previously. The concentrations were determined by comparing the yields of the reaction product from the samples with those from a standard. By varying the incident proton energy, the concentrations at different depths were measured. Such measurements give a direct indication of where the specific elements are. They also have the advantage of better depth resolution than other methods using low-energy ion beams such as Rutherford backscattering spectrometry (RBS) and particle-induced x-ray emission (PIXE). Techniques have been developed to profile various elements, such as hydrogen, carbon, fluorine, neon, etc. The $^{27}$Al($p,\gamma$) resonance at $E_p = 992$ keV has been examined earlier for profiling Al, using a NaI(Tl) detector. In the present work, we compare the nuclear reactions $^{27}$Al($p,\alpha$) and $^{27}$Al($p,\gamma$) for Al profiling.

For the present experiment, the target was a thin layer of Ga$_{1-x}$Al$_x$As on a pure GaAs substrate, prepared by MBE (molecular-beam epitaxy). The thickness of the layer was 1.0 $\mu$m, and the concentration of Al was $x = 0.23$, both determined during the MBE process. The standard target used in the $^{27}$Al($p,\alpha$) measurements was a thin layer of pure Al foil floated onto a GaAs wafer. The thickness of the foil was determined by weighing to be 0.65 $\pm$ 0.03 $\mu$m. The measurement of the $^{27}$Al($p,\alpha$) yield resulted in an energy difference of 29 $\pm$ 1 keV between the half-maximum yield points, which yields a foil thickness of 0.67 $\pm$ 0.04 $\mu$m, if the stopping power is taken from Anderson and Ziegler. The $^{27}$Al($p,\gamma$) measurements used a thick pure Al foil as the standard.

Proton beams were delivered by the 3-MV Van de Graaff accelerator at National Tsing Hua University. For the $^{27}$Al($p,\alpha$) measurements, the beam energy was varied from 1.18 to 1.25 MeV in steps of 4 keV (equivalent to depth steps of $\approx 800$ $\AA$). The beam current was typically 30 nA, and the total charge of the incident particles was 30 $\mu$C for each proton energy. In order to reduce possible heating effect during the bombardments, the incident beam was intentionally defocused to a 0.5-cm diameter.

The $^{27}$Al($p,\alpha$) resonance at $E_p = 1.183$ MeV was employed as the probe of the $^{27}$Al content of the target. This resonance has a narrow width, $\Gamma_{ab} \approx 0.66$ keV, and the cross section is approximately 2.3 mb/sr at a laboratory angle of 155°. With a $Q$ value of 1.60 MeV, the energy of the $\alpha$ particles at 155° is 2.14 MeV. The elastically scattered protons from the As atoms have a maximum energy of 1.12 MeV at the same angle. Because of the enormous counting rate of elastic scattered protons from the GaAs substrate, the $\alpha$-particle signals were completely overwhelmed by pileup of proton signals when a regular surface-barrier detector was used. A thin (8.6 $\mu$m) totally depleted surface barrier detector ($\Delta E$ detector) was therefore used for the particle spectra. The $\alpha$ particles produced by the reaction will be completely stopped in this detector, but protons can only deposit an energy of 0.7 MeV or less. The Al concentration $n(X)$ (number per unit volume) can be determined by comparing the $\alpha$ yield $Y$ from the sample with that from a standard sample,

$$n(X) = n_{st} \frac{dE/dX}{dE/dX_{st}} \frac{Y}{Y_{st}},$$

where $dE/dX$ is the rate of energy loss of the 1.183-MeV protons in the sample, and $Y_{st}$ is the $\alpha$-particle rate from a sample of known concentration $n_{st}$, and energy loss rate $dE/dX_{st}$.
The thickness determined by the energy difference at the half-maximum yields is $53 \pm 3$ keV. The stopping power of protons in Ga$_{1-x}$Al$_x$As, calculated with $x = 0.235$, yields the thickness of the Al layer as $1.03 \pm 0.05 \mu m$. The uncertainty quoted here does not include an uncertainty in the assumed stopping power, or in the number density of the GaAs crystal.

The measurements carried out with the $^{27}$Al($p,\gamma$) reaction employed the resonance at $E_{p} = 0.992$ MeV. The beam energy was varied from 0.98 to 1.06 MeV in steps of 4 keV (depth steps $\approx 700$ Å). The beam current was typically 1.0 $\mu$A, and the total charge of the incident particles was typically 1.5 mC at each proton energy. A 45-cm$^3$ Ge(Li) detector located at 55º measured the $\gamma$ rays. The $\gamma$-ray peak at 10.76 MeV and its one and two annihilation quantum escape peaks were integrated. The Ge(Li) detector was preferred over a NaI(Tl) detector for its superior resolution. Although the Ge(Li) detector has a much lower detection efficiency, it eliminates the possibility of including high energy $\gamma$ rays from nearby resonances or from possible contaminants in the target through reactions such as $^{19}$F($p,\alpha\gamma$) and $^{23}$Na($p,\gamma$). The Al profile determined by the $^{27}$Al($p,\gamma$) reaction is given in Fig. 2. The Al concentration was determined by comparing the 10.76 MeV $\gamma$-ray yield from the sample with the yield from a thick pure Al target. The stopping power of 0.992-MeV protons in the Ga$_{1-x}$Al$_x$As sample was determined in the same way as described for the case of the $^{27}$Al($p,\alpha$) measurements. Figure 2 yields an average Al concentration of $x = 0.246 \pm 0.015$ and a thickness of $1.04 \pm 0.05 \mu m$, in good agreement with the values measured by the $^{27}$Al($p,\alpha$) reaction.

From both measurements, we find that the Al concentration is at least approximately constant over the 1.0-$\mu$m thickness of the Al-containing layer. The slope of the leading edges of the profile is caused by the finite energy resolution of the incident beam. The falling edges are not as steep as the leading edges in both profiles because of the energy straggling of the protons as they travel through the target. In both Figs. 1 and 2, the solid curves are the excitation functions.
calculated for a uniform Al distribution over a depth of 1.05 μm. The simple straggling formula of Bohr was employed in the calculation although it appears to underestimate the straggling slightly. Table I compares the Al concentration and the thickness of the GaAlAs layer measured in the present experiment with the values obtained by other methods. All of the numbers agree within experimental uncertainties.

In spite of the elastically scattered proton pulse-pile-up problem that limits the rate at which data can be taken, we believe that the $^{27}$Al($p,α$) reaction is more suitable for depth profiling of Al. There are neighboring $^{27}$Al($p,γ$) resonances at 937 and 1025 keV that would limit the Al depth that can be profiled by the $E_p = 992$-keV resonance to about 0.6 μm if the 1.778-MeV γ-ray is the main contribution to the yield as was the case in earlier measurements, because the first excited state of $^{28}$Si is produced at 992 keV. Additional γ rays may also come from the possible fluorine contaminants on the target because the $^{19}$F($p,γ$) resonance at $E_p = 935$ keV has a much higher cross section than the $^{27}$Al($p,γ$) resonances. Observing the 992-keV resonance by detecting the 10.76-MeV γ-rays may also come from the $^{19}$F($p,γ$) reaction in Al profiling. This would limit the Al depth that can be profiled by the 992-keV resonance to about 0.6 μm if the 1.778-MeV γ-ray is the main contribution to the yield as was the case in earlier measurements, because the first excited state of $^{28}$Si is produced at 992 keV. Additional γ rays may also come from the possible fluorine contaminants on the target because the $^{19}$F($p,γ$) resonance at $E_p = 935$ keV has a much higher cross section than the $^{27}$Al($p,γ$) resonances. Observing the 992-keV resonance by detecting the 10.76-MeV γ-rays results in a substantial decrease in detection efficiency, and therefore forces a stronger beam to be used. Although no difficulty from the higher beam current was found in the present experiment, as judged by the agreement found between the two methods, possible effects from target heating by the higher beam, implantation of beam hydrogen, and increased radiation damage might be important enough in specific applications to lead to a preference for the $^{27}$Al($p,α$) reaction in Al profiling.

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Effect of organic additives to a nitrogen laser
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Contrary to recent predictions, it has been observed that the addition of small quantities of hydrogen, ethanol, and benzene to nitrogen reduce the output power of a nitrogen laser. N,N-dimethylamine enhances the output power of the laser by 25%. A Penning ionization process is proposed as a mechanism for quenching the $B^3Π_g$ state of nitrogen.

Ever since the discovery of the nitrogen UV laser by Heard in 1963, it has been a subject of investigation because of its relative simplicity. This laser has undergone many modifications to obtain higher output powers. A large part of the effort in this direction has been towards modifying the electrode design and the electrical circuitry. Helium and argon have been used as buffer gases to obtain higher output powers at total operating pressures of atmospheric pressure and above. Also, there are a number of reports available in literature, where they have used fluorine containing compounds as additives to nitrogen and have obtained an increase in output power up to 30% on the 337.1-