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A GaAs Detector for Dark Matter and Solar Neutrino Research.

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Abstract

The ability to produce large GaAs crystals with the requisite electronic properties to be fabricated into charged particle and photon detectors would provide a detector medium that would find numerous applications in both applied and fundamental research. Various applications would likely include x-ray detectors on satellites, environmental monitoring, medical imaging, bore hole mining spectroscopy, searches for dark matter, and solar neutrino research. We have carried out the development of GaAs detectors using two commercial crystal growing techniques. We have shown it should be able to grow detectors with 20 cm^2 area and a depletion depth of 1 mm. Detectors of this size would find immediate applications in high-resolution, room temperature, low energy gamma ray measurements. We have also arrived at an understanding of the limitations of the common techniques used to grow GaAs and have determined that it should be possible to produce larger detectors using proprietary methods.

Background and Research Objectives

The ability to produce large GaAs crystals with the requisite electronic properties to be fabricated into charged particle and photon detectors would provide a detector medium that would find numerous applications in both applied and fundamental research. Various applications would likely include x-ray detectors on satellites, environmental monitoring, medical imaging, bore hole mining spectroscopy, searches for dark matter, and solar neutrino research. GaAs detectors have two primary advantages: first, operation with high resolution (a few keV) at room temperature, and second, specific nuclear properties that are of direct interest in fundamental physics research such as dark matter and solar neutrinos. Clearly the ability to have a high resolution, room temperature gamma ray detector would find great use in a number of the Laboratory's missions, including monitoring of nuclear materials and nuclear safeguards as well as environmental monitoring, biophysics, and basic research

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Importance to LANL's Science and Technology Base and National R&D Needs

The applications of new detector technologies in a variety of fields is being pursued around the world. A number of novel photon and charged particle detectors are now in various stages of development. These include the well-known Si, Si(Li), and hyper-pure Ge detectors that are being used in an increasing range of specialized designs. Detector systems based on Si tend to be used in applications requiring small detectors with very good energy resolution and can provide extremely precise position resolution. Other detectors that have been developed for photon detection (often from initial research carried out for particle physics applications) include sodium iodide, cesium iodide, bismuth germanate, barium fluoride, hyper-pure germanium (HPGe) and others. A wide range of possible semiconductor detectors are also being developed for photon detection including PbS, PbSe, InSb, InGaSb, CdHgTe, ZnCdTe, and PtSi. However, to date HPGe detectors are still the detector of choice for most applications requiring high-resolution measurements of gamma rays in the 100 keV – 10 MeV range. While HPGe detectors have very good energy resolution, they have one major drawback: the need for cryogenic cooling to liquid nitrogen temperature in order to become semiconducting. GaAs detectors can also provide very good energy resolution (about 40% worse than HPGe detectors) but are semiconducting at room temperature. This obviates the need for cooling to liquid nitrogen temperature and thus reduces both the cost and effort to construct and operate the detectors. We believe the advantage of room temperature operation greatly outweighs the somewhat poorer energy resolution attainable and that GaAs photon detectors would find immediate and wide-ranging applications in many fields. Those fields are likely to include x-ray and gamma ray detection on satellites, medical imaging, environmental monitoring, bore-hole mining spectroscopy, nuclear and particle physics, and the nuclear industry. In particular, such detectors are certain to be of interest to the Threat Reduction efforts at LANL.

In the area of fundamental physics, the specific nuclear properties of GaAs, in addition to its detector properties, offer promise for addressing two of the most outstanding issues in modern physics: 1) What is the Dark Matter that comprisies most of the mass of the Universe? and 2) Do neutrinos have a finite mass? Ga is one of the few nuclei in which inverse beta decay from the dominant, low-energy p-p solar neutrinos can occur. This effort supports the basic research efforts at LANL.

Scientific Approach and Accomplishments

Measurements of the p-p, pep, and ^{7}Be neutrinos appear particularly important in resolving the solar neutrino problem. In the primary fusion process in the Sun, there are two processes: $p + p \rightarrow d + e^{-} + \nu_e$ and $p + e^{-} + p \rightarrow d + \nu_e$. The relative branching ratio (2.4×10^{-3}) for p-p and pep neutrinos depends essentially only on phase space. The production of ^{7}Be neutrinos is via the $^{7}Be + e^{-} \rightarrow {}^{7}Li + \nu_e$ reaction. The ^{7}Li daughter can be left either in the ground state or in the first excited state at 478 keV. This results in neutrinos being emitted at energies of 862 keV and 384 keV with branching ratios of 91.7% and 9.3% respectively. Again, this branching ratio depends only on phase space. Thus, a model independent determination of the origin of the solar neutrino problem could be made by measuring these branching ratios. If no new physics is occurring in the Sun, the ratios are determined by laboratory measurements. If new physics is occurring in the Sun in the form of nonadiabatic MSW oscillations, the p-p and 384 keV ^{7}Be neutrinos are essentially unaffected while the pep and 862 keV ^{7}Be neutrinos are just in the region where the suppression is changing most rapidly. Thus, the comparison of the amplitudes of the low energy solar neutrinos could provide the most sensitive determination possible of the MSW oscillation parameters.

One can also make a model-independent determination of the central temperature in the Sun from the widths of the pep and ^{7}Be lines, their energy shifts (relative to the laboratory) and the change in the endpoint energy of the p-p neutrinos. As the region over which each of the nucleosynthesis reactions occurs differs, one obtains an average temperature at different solar radii associated with each of the neutrino sources. This provides the possibility to roughly map out the radial temperature distribution in the center of the Sun.

In order to measure the p-p neutrinos and the pep and ^{7}Be line sources, one requires an electronic detector with a low threshold, very good energy resolution, and low backgrounds. In addition, there are no long-lived cosmogenically-produced isotopes of either Ga or As and it should be possible to make GaAs detectors with extremely low backgrounds. In terms of the widest range of physics which could be addressed, it appears that the best detector would be one based on GaAs, as it is the only detector capable of measuring both charged and neutral currents as well as elastic scattering for the p-p, pep, and ^{7}Be neutrinos with high event rates, excellent energy resolution, and very low backgrounds.

In addition, there are no long-lived cosmogenically-produced isotopes of either Ga or As and it should be possible to make GaAs detectors with extremely low backgrounds.

Thus, GaAs seems ideally suited to a search for Dark Matter in the form of Weakly Interacting Massive Particles and for studies of solar neutrinos. If we are able to resolve the origin of Dark Matter, this would certainly rank as one of the most important discoveries in modern physics. In the field of solar neutrinos, GaAs may provide what will be the "ideal" detector as it can study both particle physics and astrophysics issues with unprecedented precision.

A number of models for cold dark matter have been proffered, but perhaps the most naturally attractive is WIMPs. This type of dark matter is attractive because if one calculates the number density of WIMPs produced in the Big Bang , one finds the annihilation cross section of WIMPs required to account for closure density is just at the weak interaction scale. In addition, if one invokes SUperSYmmetry (SUSY), one finds that the lightest stable supersymmetric partner (the neutralino) is predicted to have a mass and annihilation cross section that is just what is required to solve the dark matter problem. While there is no direct evidence for SUSY, there is indirect evidence from LEP which shows that it is necessary to invoke SUSY in order to have the weak, electromagnetic, and strong interaction coupling constants come together at the GUT scale of 10^{15} GeV. Thus, it is at least plausible that the dark matter may be in the form of WIMPs.

WIMPs can be detected in the laboratory by observing their elastic scattering from nuclei. Nuclear recoil from WIMP interactions have several signatures which allows one to separate a WIMP recoil signal from other backgrounds (such as nuclear recoil from a fast neutron). With WIMP masses in the few GeV to 100 GeV range, one can observe recoil nuclei with energies in the keV to tens of keV range. The recoil energy depends on both the mass of the WIMP as well as the mass of target nucleus while the recoil rate depends on the scattering cross section. As the WIMPs are essentially at rest in the rest frame of the Universe, the relative motion of the WIMPs that we observe comes from the rotational velocity of our solar system around the galaxy (at about 220 km/s) and the rotational velocity of the Earth around the Sun (at about 25 km/s). Thus, there is an annual variation of the nuclear recoil spectrum, depending on whether the Earth is moving in the same direction as the galactic rotation or in the opposite direction. The recoil direction is also defined to be in the opposite direction of the galactic rotation. The best limits on the abundance of WIMPs to date comes from using large solid state Ge double beta decay detectors that observe the recoiling Ge nuclei. At present, the best of these experiments is just starting to reach the sensitivity required to reach into the cross-section range predicted by SUSY. These experiments are limited primarily by backgrounds at the very low energies required to observe the nuclear recoils.

GaAs has a number of advantages: the density is reasonably high (5.317 gm/cm^3), the band gap in GaAs is 1.43 eV (compared to 0.74 eV for Ge and 1.12 eV for Si), and the average Z (40) is rather high, providing a good stopping power. Due to the higher band gap energy, a GaAs detector can be operated ar room temperature. The energy resolution could likely be 2–3 keV in the region of interest (a few hundred keV to a few MeV), and the production process of single crystals effectively suppresses incorporation of radioisotopes such as U and Th.

GaAs and GaP offer a number of advantages as potential WIMP detectors. First, room temperature operation greatly simplifies the design and operation of a detector system. Second, it is possible to construct a detector comprised of alternating layers of GaAs and GaP detectors in the same shield (and thus are exposed to the same external background at the same time). As the GaAs and GaP crystals will all be grown with the same technique and fabricated into detectors with the same techniques, the internal backgrounds should be reasonably similar in both detectors. In addition, as the detector array is composed of many relatively small detectors, the detector array will be self-diagnosing in terms of internal backgrounds. If a potential WIMP signal is observed in the GaAs detector array, then it is possible to predict the signal that should be observed in the GaP detector array. This will provide a powerful means of confirming the existence of a WIMP signal. Third, there are no long-lived isotopes of Ga, As, or P so that internal backgrounds are estimated to be low. Finally, all of the isotopes of Ga, As, and P have nonzero spin, thus providing 100% sensitivity to spin-dependent WIMP interactions.

Small GaAs Schottky diode detectors have been constructed from liquid phase epitaxy GaAs have achieved 2.2 keV FWHM at 0 C for the 59 keV ^{241}Am gammas. [1] Larger detectors have also been fabricated, but with rather poor energy resolution. [2-4] The poorer resolution achieved with GaAs using the LEC process is due primarily to impurities, grain boundaries, defects, imprecise stoichiometry, and inhomogenieties in the ratio of Ga to As in large crystals. A large effort to develop commercially available semi-insulating bulk GaAs has been carried out over the last two decades (mostly by high energy and nculear physicists). The primary requirement in developing a usable GaAs detector is to reduce the level of electrically active defects to a point where they do not appreciably affect charge collection over a drift distance of many centimeters. In addition having to deal with the same problems that are faced in the production of HPGe detectors, since GaAs is a III-V semiconductor, there are native defects that have no analog in Ge. The most serious of these defects (EL2) is typically found at a density level of several x 10^{15}/cm^3 and it is primarily this defect that limits the distance over which charge can be collected.

While progress was being made in reducing these problems, it was clearly necessary to further develop the LEC techniques before one could contemplate constructing a large detector.

The need for further development of commercial GaAs production led us to propose an effort to develop GaAs detectors for use in dark matter and solar neutrino research. In this effort we have carried out a very comprehensive study of the growth of the two most common means of producing bulk semi-insulating GaAs (Liquid Encapulsated Czochralski and Horizontal Bridgeman).

A collaboration between Los Alamos National Laboratory, the Institute for Nuclear Research, Girdemet, the Joffe Institute of Solid State Physics in St. Petersburg, and Moscow State University was formed to develop GaAs detectors. We drew on more than 20 years of expertise in growing GaAs at Giredmet, purification of Ga at the INR, solid state spectroscopy at Moscow State University, detector fabrication and measurement at the Joffe Institute, and low background capabilities and detector technology at Los Alamos. We are able to grow GaAs crystals very cost effectively at Giredmet under carefully controlled conditions.

We have grown more than 20 1-kg ingots of GaAs, characterized their electrical properties, and made some 400 micron-thick wafers into detectors. In order to understand the limitations on possible detector thickness, we have studied the GaAs crystals and the detectors made from them in detail using a variety or measurement techniques.
We can now extrapolate the performance and conclude that we should be able to fabricate detectors with a usable thickness of up to 1 mm.

We have found that there are intrinsic factors limiting the reduction of electrically active defects to the level required to produce large GaAs detectors. While we have substantially improved on what has been done previously, it seems that these techniques are limited to making detectors less than 1 mm thick. However, now that we have an understanding of the limiting factors for growing suitable GaAs, we plan to pursue the growth of GaAs with a proprietary technique that should not be limited by the same factors that we discovered with commercial growing techniques.

Publications

T.J. Bowles et al., "A GaAs SOLAR NEUTRINO DETECTOR", to be published in Proc. of the Xth International School "PARTICLES and COSMOLOGY" April 19 - 25, 1999, Baksan Valley, Kabardino-Balkaria, Russia

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