Face dependence of the spin polarization of photoelectrons from NEA GaAs (100) and (110)

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We present measurements of the spin polarization P of photoelectrons from negative electron affinity (NEA) GaAs (100) and find $P = 43\%$ at a photon energy of 1.57 eV. This contrasts with a maximum $P = 21\%$ measured by Erbudak and Reihl for NEA GaAs (110), which led them to conclude that NEA and high P exclude each other. This difference in P is important for sources of polarized electrons employing photoemission from GaAs. We suggest that the origin of this difference may be connected with differences in the photoelectron emission process at the two faces, as calculated by Burt and Inkson.

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Photoemission from negative electron affinity (NEA) GaAs provides an excellent source of spin-polarized electrons. This type of source has recently found success in such diverse applications as the parity violation experiment carried out at the Stanford Linear Accelerator Center[1] and spin-polarized low-energy electron diffraction carried out at the National Bureau of Standards.[2] Theoretically, a spin polarization of 50% is possible as a result of the selection rules for photoexcitation with circularly polarized light of photon energy just greater than the GaAs band gap. The photoelectron spin polarization is easily reversed by reversing the sense of the circular polarization of the incident light. The GaAs vacuum level can be lowered by applying cesium and oxygen to the surface, making it a very efficient photoemitter. These characteristics of spin-polarized photoemission from GaAs have been described previously.[3-5]

In a recent paper, Erbudak and Reihl[6] presented spin-polarized photoemission measurements from (110) GaAs surfaces activated to obtain a negative electron affinity for which they found a maximum polarization of 21%. They concluded that the high quantum yield associated with a negative electron affinity and a high polarization exclude each other and that it is undesirable to operate in an NEA mode. Because of the interest in GaAs as a source of spin-polarized electrons, it is important to point out that their conclusion may apply only to the (110) NEA surface. We measure, in contrast, a polarization of 43% from NEA GaAs (100) surfaces and operate in the NEA mode with correspondingly greater quantum yields. In this paper we present these new measurements on NEA GaAs (100) and suggest how the difference in polarization measured on the (110) and (100) surfaces can be understood.

The experimental data are shown in Fig. 1. Note that both surfaces exhibit the steep rise in quantum yield Y and sharp knee at threshold characteristic of negative electron affinity photocathodes.[7,8] In spite of the strong similarity between the photoyield curves for the two faces, there is a striking difference in the measured polarizations near theshold, which are referred to the right-hand axis in Fig. 1. Our yield measurements were made with a monochromatized white light source whereas the polarization measurement was made at the 1.57-eV photon energy of a GaAlAs diode laser. The apparatus and method of polarization measurement are discussed in Ref. 2. Erbudak and Reihl measured the polarization P as a function of photon energy $\hbar\omega$ and found the maximum P to occur at $\hbar\omega = 1.55$ eV, with less than 5% deviation over the range $1.50 < \hbar\omega < 1.60$ eV. The (110) and (100) samples were doped p type at 1×10^{19} and 5.6×10^{18} cm^{-3}, respectively. The (110) GaAs crystals were cleaved in ultrahigh vacuum. The (100) GaAs was a polished wafer which was heat cleaned in ultrahigh vacuum. Both surfaces were activated at room temperature by applying Cs and O_2. The measurements of the yield and the spin polarization for the (110) surface were made at 77 K and for the (100) surface at 110 K.

The measured spin polarization P may be less than the 50% theoretical polarization if the photoexcited electrons undergo a spin relaxation (depolarization) during the life-

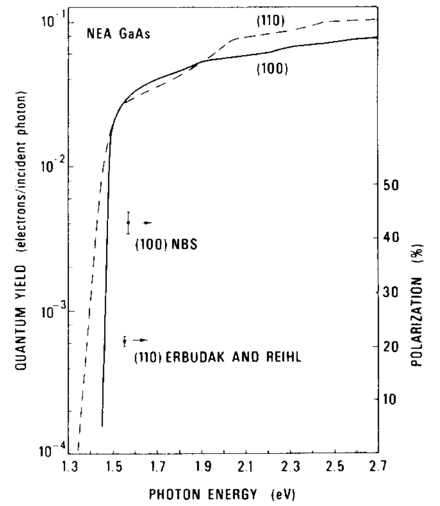

FIG. 1. The quantum yield for an NEA (100) surface is compared to the yield from an NEA (110) surface measured previously (Ref. 6). Although the yield curves are quite similar, there is a striking difference in the spin polarization which is found to be 43 and 21% at photon energies just above the band gap for the (100) and (110) faces, respectively (polarization points referred to scale on right-hand axis).

time of the excited electron in the crystal before emission. The electron lifetime is not an intrinsic parameter but is influenced by sample-dependent properties such as deep traps and surface recombination. The photoelectrons could also be depolarized by a spin-exchange scattering at the surface activation layer as proposed by Erbudak and Reihl. A recent calculation by Burt and Inkson[9] of the face dependence of photoemission from NEA GaAs provides an attractive explanation of the observed differences in P from NEA GaAs (110) and (100), although we cannot rule out material differences or details of the surface cleaning and activation as possible causes.

Burt and Inkson calculated the transmission coefficient T at different faces as a function of band bending for electrons in the Γ minimum. T is defined as the probability of transmission for each encounter with the vacuum interface. They did not explicitly consider the nature of the Cs-O activation layer. Rather, a potential step was used which gave a value of 0.2 eV for the NEA. We are interested in the (110) and (100) faces where the calculated T is 0.03 and 0.44, respectively, for a typical band bending of 0.25 eV. The order-of-magnitude difference in T was attributed to the very large anisotropy of the wave functions at Γ. Even though the details of the Cs-O layer are ignored, this calculation is suggestive of a fundamental difference in the emission process at the (110) and (100) faces of GaAs.

The large difference in the transmission coefficients at the vacuum interface is not reflected in the experimentally determined total escape probabilities $\mathscr{P}_{\rm esc}$ of the photoelectrons.[8] For commercial-quality photocathodes, James *et al.*[10] measured $\mathscr{P}_{\rm esc}$ of 0.307 and 0.317 for the (110) and (100) faces, respectively. $\mathscr{P}_{\rm esc}$ can be similar for the two surfaces, even though T is quite different, because electrons which are reflected at the (110) surface can be turned around again in the band-bending region, as discussed by James and Moll[7] and Clark.[11] Such electrons can proceed again to the surface for another attempt at transmission. This process can be repeated many times to give a sizeable overall $\mathscr{P}_{\rm esc}$ for the (110) surface even though the transmission probability for each encounter with the surface/vacuum interface is small.

The question arises as to why there is not a similar increase of $\mathscr{P}_{\rm esc}$ for the (100) surface by multiple transmission attempts. A possible explanation suggested by Burt and Inkson is again the anisotropy of the wave functions at Γ which causes the surface recombination velocity to be high for the (100) face but low for the (110) face. Thus, we have a picture of the (110) face where an electron makes repeated attempts at transmission as it bounces back and forth in the band-bending region. For the (100) face the electron is very likely to recombine if it is not transmitted, and multiple escape attempts do not play a large role.[12]

This model for the electron-escape process at the (110) and (100) surfaces provides two possible sources of the difference in the measured photoelectron spin polarization. The spin relaxation time in the band-bending region has been observed in luminescence measurements at liquid-nitrogen temperature to be less than the bulk spin relaxation time.[13] The depolarization of (110) photoelectrons could be enhanced owing to the greater time the electrons spend in the band-bending region, the region of more rapid depolarization.

A second mechanism which could give rise to the difference in the photoelectron spin polarization is the spin-exchange scattering discussed by Erbudak and Reihl. The spin-exchange scattering cross section between electrons and alkali atoms is large and increases rapidly at low energies such as those of the escaping photoelectrons.[14] If there is some nearly-atomic-like Cs in the Cs-O layer, it could be a large source of depolarization via spin-exchange scattering. We can now see why the depolarization could be large for the (110) face but small for the (100) face. Electrons at the (110) face pass through the Cs-O layer to be reflected at the large potential jump at the Cs-O/vacuum interface, return back thru the Cs-O layer, and become turned around in the band-bending region for more attempts at transmission and more passes through the Cs-O layer.[15]

Erbudak and Reihl have demonstrated that the low polarization disadvantage of the NEA (110) surface can be overcome by using a surface with a positive electron affinity. The electrons are emitted from the L minima at 0.3 eV higher kinetic energy than at Γ. The wave functions at the L minima do not have the same anisotropy as at the Γ minimum, which along with the higher kinetic energy leads to a reduction in the spin depolarization. Operating in the positive electron affinity mode, Reihl *et al.*[16] have achieved $P = 35\%$ and a figure of merit $P^2Y \simeq 1\times10^{-3}$. This can be compared to our results using NEA GaAs (100) where we find $P = 43\%$ and a figure of merit $P^2Y \simeq 6\times10^{-3}$.

In summary, we have shown that in contrast to the conclusion of Erbudak and Reihl, high spin polarization and negative electron affinity need not be mutually exclusive. We find that NEA GaAs (100) gives a high polarization of 43%, a high yield, and consequently, a higher figure of merit. We have shown that the model calculations of Burt and Inkson show how the spin-exchange scattering induced depolarization suggested by Erbudak and Reihl could lead to different spin polarizations for NEA GaAs (110) and (100) faces. As more experience is gained with GaAs in polarized electron sources, the possible dependence of polarization on material and cathode processing can be ascertained. Both NEA GaAs (100) and positive electron affinity GaAs (110) are suitable for sources of spin-polarized electrons. Which crystal face is preferred may ultimately depend on available light sources or laboratory preference between cleaving a crystal and heat cleaning a wafer. In either case, the GaAs spin-polarized electron source has many advantages over competing types of sources.

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Niobium silicide formation induced by Ar-ion bombardment

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The effect of Ar-ion bombardment on evaporated–Nb-on-Si systems has been investigated with He backscattering and x-ray-diffraction measurements. High-dose bombardment with energetic Ar ions was found to induce intermixing between Nb and Si in the form of $NbSi_2$. This effect has strong dependence on temperature during bombardment, although it cannot be explained as enhanced diffusion due to radiation damage or ion-beam heating.

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In recent years, thermal reactions between thin metal films and Si substrates attracted increasing attention for their technical importance. Besides heat treatment, ion bombardment can also cause thin-film reactions.[1] Lee *et al.*[2] reported that amorphization of the Si surface by ion bombardment enhanced the mutual migration rate with Al films. More directly, Lee *et al.*[3] and Van der Weg *et al.*[4] found that ion bombardment induced intermixing in the Pd/Si systems, if the bombarding ions had enough energy to penetrate the Pd film. Recently, Tsaur *et al.*[5] investigated Pt, Ni, and Hf silicide formation induced by inert-gas-ion bombardment and observed a square-root dependence of Pt_2Si thickness on ion dose.

We have investigated the effect of ion bombardment on the Nb/Si system, in which thermal intermigration between Nb and Si is known[6] to occur only at higher temperatures than in Pd/Si or Al/Si. As a result of our experiment, bombardment with Ar ions was found to induce intermixing and silicide formation in that system. A similar effect caused by Si-ion bombardment was recently reported.[7]

Niobium films were deposited onto (111)-oriented Si wafers by electron-beam heating at a deposition rate of about 100 Å/min. Two different film thicknesses were used: 760 and 440 Å. Just before loading in the vacuum chamber, Si substrates were cleaned in organic solvents and hot HNO_3, and were slightly etched in dilute HF. The vacuum was pumped down to 2×10^{-8} Torr and was about 2×10^{-7} Torr during evaporation.

Bombardments with Ar ions were carried out at various temperatures with a typical dose rate of about $1\times10^{13}/\mathrm{cm}^2\,\mathrm{sec}$. Doses used were in the range from 1×10^{16} to $6\times10^{16}/\mathrm{cm}^2$. Sample surfaces were tilted 7° from the normal incidence of the ion beam. For comparison, annealing of both unbombarded and room-temperature-bombarded samples was also performed in vacuum.

Composition profiles were analyzed by measuring the energy spectra of He ions with an initial energy of 1.5 MeV backscattered to an angle of 160°. Diffraction patterns of Cu-$K\alpha$ x rays were taken with a conventional Bragg-Brentano diffractometer to identify phases of the layers produced.

Figure 1 shows backscattering spectra for 760-Å Nb/Si samples bombarded with 200-keV Ar ions at various temperatures. In Fig. 1(b), it is clear from the apparent steps observed in both Nb and Si components that bombardment with 5×10^{16} Ar ions/cm^2 produces intermixing of Nb and Si even at room temperature (RT). However, as shown in Fig. 1(c), when bombardment is carried out at 300 °C, it can produce an intermixed layer several times thicker than bom-