and near the front surface of the sample. The carrier density falls off cosinusoidally away from the grating peak along the sample surface and exponentially into the sample bulk.

We have used a variation of the transient grating technique to measure the picosecond dynamics of laser-induced transient gratings that are produced in germanium by direct absorption of 35-psec optical pulses at 1.06 μm. We have measured subnanosecond grating lifetimes for peak free-carrier densities of $\sim 5 \times 10^{19}$ cm^{-3} and for four grating spacings, 6.8, 11.5, 15.7, and 22.7 μm. A linear diffusion-recombination model provided a good fit to the experimental data for all grating spacings and allowed the extraction of an ambipolar diffusion coefficient of 53 cm^2/sec at a sample temperature of 295 K and of 142 cm^2/sec at 135 K. The recombination lifetime was estimated to be much greater than 1 nsec in both cases.

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Effect of substrate surface treatment in molecular beam epitaxy on the vertical electronic transport through the film-substrate interface

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We have grown n^+-GaAs films using Sn or Ge doping on n^+-GaAs substrates by molecular beam epitaxy and studied the vertical electronic transport through the film-substrate interface. An interfacial layer with high resistance and a nonlinear *I-V* characteristic is observed whenever the substrates have been sputter-cleaned and annealed prior to the growth. Similar results are observed for the nonsputtered substrates with a high surface coverage of carbon. Such an interfacial layer can be eliminated in both cases by a predeposition of a Sn monolayer prior to the growth of the n^+-GaAs layers.

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Molecular beam epitaxy (MBE) has recently been used for the fabrication of various III-V semiconductor devices on GaAs substrates.[1] Substrate treatment in the MBE chamber prior to the film growth is important to the quality of the films grown. For example, we have observed generation of dislocations due to surface contaminants, which propagate into the subsequent growth.[2] An effective way to remove such surface contaminants, mostly carbon, is by ion sputtering. The substrate is then annealed in an As ambient to remove the surface damage caused by sputtering and to restore its surface crystallinity. We have observed, however, an interfacial layer with high resistance and a nonlinear *I-V* characteristic for the films grown on such substrates. We have also observed a similar interfacial layer for cases where the substrates were not sputter cleaned but had a high surface coverage of carbon. A similar interfacial layer has also been reported for the GaAs films grown by vapor phase epitaxy and liquid phase epitaxy.[3,4] The presence of such an interfacial layer is detrimental to the vertical transport devices for which electrical transport through the film-substrate interface is involved. In this letter we report our observations on such interfacial layers and show that they can be eliminated by a predeposition of a monolayer Sn prior to the growth of GaAs layers.

The MBE growth of GaAs has been described before.[5] n^+GaAs substrates, (100) oriented and Si doped to (1–2)$\times 10^{18}$ cm^{-3}, were degreased and chemically etched in H_2SO_4:H_2O_2:H_2O prior to loading into the MBE chamber. Auger spectroscopic measurements indicate that oxygen and carbon are the major surface contaminants. Surface oxygen can be removed by an *in situ* heat treatment to ~ 550 °C. The presence of carbon and its removal depend strongly on the etching procedure and wafer handling prior and subsequent to their introduction into the MBE chamber. We observed, for example, that in spite of careful etching procedures in clean hoods, a small amount of carbon [$\sim$ 5–10% of the Auger intensity of the O (*KLL*) line] was invariably detected and could not be reduced appreciably by subsequent thermal removal of the oxide. However, a thermal treatment in UHV to $\sim$350 °C prior to the Auger measurement or exposure to other ionizing sources, drastically reduced the carbon contamination, sometimes below the detection limit of the instrument. We interpret these results as indicative of surface contamination after the etching procedure. The subsequent thermal removal is only possible if the contaminant is not converted to a more stable form by the ionization source. For this latter case, sputtering is the only alternative to the removal of residual carbon. For convenience we call these sputter-cleaned surfaces type I substrates, whereas those cleaned thermally are type II substrates. For the type I substrate, sputtering with Ar ions was performed at an Ar pressure of 5×10^{-5} Torr, with a beam voltage of 3 kV and emission current of 30 mA. After sputtering, the substrate was annealed at 600 °C in an As ambient to remove surface damage and restore crystallinity. Substrate temperature used for growth was $\sim$580 °C.

For the studies of vertical electronic transport through the film-substrate interface, n^+-GaAs films, 2–3 μm thick, were grown on GaAs substrates cleaned by sputtering. GaAs films were doped with either Sn or Ge in the range of 10^{18}–10^{19} cm^{-3}. Ohmic contacts using Au-Ge-Ni were evaporated on the back of the substrate and on the film surface, followed by patterning the front contact to 100×100-μm^2 squares. The contacts were alloyed at 450 °C for 30 sec in forming gas. The samples were mesa etched in steps of $\sim$0.5 μm, and top-to-bottom *I-V* characteristics measured at each step. These structures are shown schematically in Fig. 1. The *I-V* characteristic remained ohmic for the structures shown in Figs. 1(a)–1(b), i.e., before the film-substrate interface was etched through. However, once the interface became incorporated into the mesa, as Fig. 1(c) shows, a high resistance and nonlinear *I-V* characteristic is observed. Such an *I-V* characteristic is shown in Fig. 2.

The above results indicate the presence of a high-resistance interfacial layer between the film and the substrate. Because of the large area of the interface in samples of Figs. 1(a) and 1(b), the high resistance is not observed. We have observed such an interfacial layer for the films grown on GaAs substrates cleaned by sputtering (type I substrate), and those grown on nonsputtered substrates with a high surface carbon coverage of about a fraction of a monolayer. In both cases both Sn and Ge were used as dopants. For the films grown on nonsputtered substrates with low surface carbon (type II substrate), a similar interfacial layer was observed when Sn was the dopant but not when Ge was used. The case with Sn could be related to the depletion region reported at the film-substrate interface.[6]

Our studies have thus established the effect of sputtering prior to the film growth on the creation of a high-resistance interfacial layer. The presence of a high surface carbon coverage is seen to cause a similar effect. It seems probable that the sputtering process has created damage at the substrate surface which is not completely removed by annealing. The residual surface damage could act as traps for the charge carriers and account for the high-resistance interfacial layer observed. *C-V* measurements, as described later, have shown a depletion region at the film-substrate interface for such structures. The presence of high surface carbon can also be the source of high defect density at the interface, which is detrimental to the vertical transport through the film-substrate interface.

To eliminate such an interfacial layer, we have developed a technique of monolayer Sn predeposition to saturate the defect-related trapping states. After sputter cleaning and annealing, a monolayer of Sn was deposited prior to the growth of n^+-GaAs layers. The films thus grown show an ohmic *I-V* characteristic for the mesa-etched structures of Fig. 1(c). A typical *I-V* characteristic is shown in Fig. 3. This technique has also been successfully applied to the films

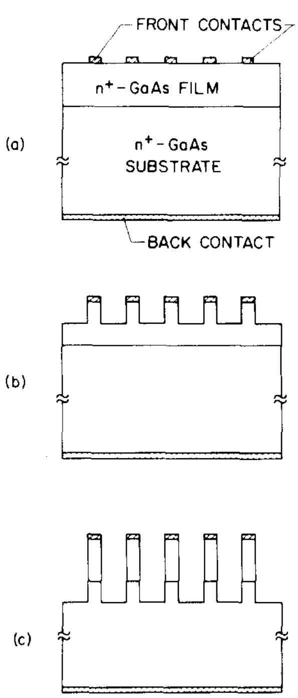

FIG. 1. Schematics of the structures used for *I-V* measurements. (a) a 2-μm n^+-GaAs film on n^+-GaAs substrate with alloyed contacts; (b) 1 μm etched, and (c) 3 μm etched.

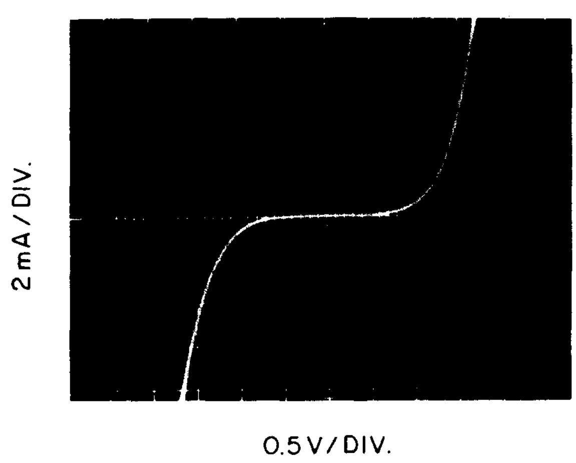

FIG. 2. *I-V* characteristic of a 2-μm Sn-doped GaAs film ($n\sim1\times10^{19}$ cm^{-3}) deposited on a sputter-cleaned GaAs substrate. Mesa structure size: 100×100 μm^2.

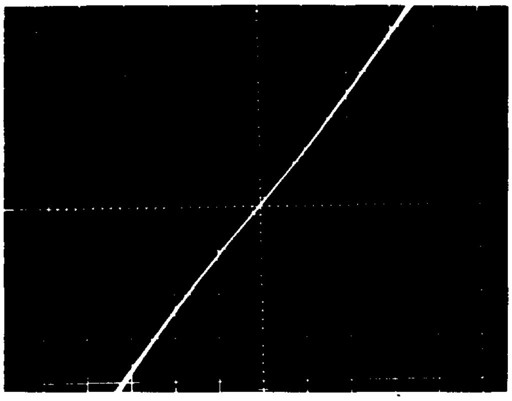

FIG. 3. I-V characteristic of a 2-μm Sn-doped GaAs film ($n \sim 1 \times 10^{19}$ cm^{-3}) deposited on a sputter-cleaned GaAs substrate with a predeposition of monolayer Sn. Mesa structure size: $100 \times 100\ \mu m^2$.

grown on nonsputtered substrates with high surface carbon coverage, and to those grown on the type II substrates using Sn doping. The last case thus resembles the work for the growth of a continuously Sn-doped GaAs by MBE.[6]

The amount of Sn needed to achieve ohmic interfacial behavior depends on the density of defect-related trapping states caused by either sputtering or surface carbon. We have made C-V measurements on a sample grown on the sputter-cleaned substrate. The electron concentration of the GaAs film is 3×10^{18} cm^{-3}, doped with Ge. We obtain a depletion width of 360 Å. This corresponds to a trapping state density of $\sim 10^{13}$ cm^{-2}. The use of a monolayer of Sn is thus sufficient to saturate the trapping states of such a magnitude at the interface. The remaining Sn will dope the overgrown GaAs to $\sim 10^{19}$ cm^{-3} for a certain layer thickness, as we have observed. Thereafter, the Sn doping decreases exponentially as recently reported.[7]

In summary, we have shown that the sputter-cleaning procedure for the GaAs substrates in MBE creates an interfacial layer of high resistance and nonlinear I-V characteristics. Similar interfacial layers are also present for the films grown on nonsputtered substrates with high surface carbon coverage. This interfacial layer is detrimental to the vertical transport devices, where electrical transport through the film-substrate interface using a mesa structure is involved. We have successfully eliminated such an interfacial layer with a predeposition of a monolayer Sn prior to the growth of GaAs films on both types of substrates.

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