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Strained-Layer Electronics and Optoelectronics

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Strained-layer epitaxy involves more than the dislocation-free growth of dissimilar materials: effective strained-layer epitaxy exploits lattice-mismatch-induced strain to fine-tune material properties. This paper describes strained-layer epitaxy and describes its application to electronic and optoelectronic device to improve performance.

Strained-Layer Epitaxy and Critical Thicknesses

The highest-performance compound-semiconductor devices rely on dislocation-free epitaxial combination of materials with differing energy gaps. Freedom from the tyranny of having to match the bulk lattice constants of the epitaxial materials results in the greatest possible flexibility in realizing such heterojunction combinations. Mismatched layers are neither new nor uncommon: modern integrated-circuit technologies exploit the interface between two materials which differ substantially in their equilibrium atomic spacings: namely, silicon and silicon dioxide. Remarkably, despite early pioneering work [1, 2], it took Osbourn's insight in 1982 [3] that strains could fine-tune band structure to spark active interest in strained-layer epitaxy. Dislocation-free epitaxy of lattice-mismatched materials is possible because it requires only meV of energy to distort atoms from their equilibrium positions, while eV of energy are required to break atomic bonds to nucleate dislocations. Thus, a considerable number of atoms can be displaced from their equilibrium positions before nucleation of dislocations becomes energetically favored. Ultimately, the greater the thickness of the mismatched layer (the more atoms displaced), or the further the atoms in the epitaxial layer are distorted from their equilibrium positions (that is, the greater the mismatch between the bulk lattice spacings), the sooner this limit will be reached. These considerations form the basis for calculations of critical layer thicknesses. Unfortunately, confusion regarding the determination of critical layer thicknesses has arisen because modern growth occurs under non-equilibrium (kinetically controlled) conditions. As-grown strained layers may exceed limits set by equilibrium thermodynamics by an order of magnitude. Only when sufficient energy is provided, e.g., by annealing at temperatures above the growth temperature or by direct ion bombardment, can thermodynamic critical thicknesses be determined [4]. Experiments support the limits determined by Matthews and Blakeslee [2] for the two cases they considered: an infinitely repeating superlattice or a single strained layer at a free surface. Unfortunately, these

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rarely occur in practice. Typical strained-layer devices include an epitaxial region lattice-mismatched to its substrate, capped at the top surface with a finite thickness of unstrained material. Such structures were considered by Tsao and Dodson [5], who found that the combination of strained and unstrained material can be modelled as a surface strained layer characterized by a thickness-averaged effective strain. A practical guide for applying these calculations was recently presented [6].

Strain Effects on Electronic Band Structure

The effect of strain in tailoring band structure is often as strong a motivation for the use of lattice-mismatched layers as is the dislocation-free incorporation of mismatched materials. The in-plane (biaxial) lattice strain is equivalent to a hydrostatic compression plus an opposing uniaxial strain. Since the hydrostatic compression retains the symmetry of the lattice but changes the interatomic spacing, it merely alters the positions of the energy bands. In contrast, the uniaxial component reduces the symmetry of the lattice and thus splits degenerate energy levels, most notably the zone-center degeneracy of the valence bands, and further repositions the energy bands. Best agreement between calculations and experiment [7] have been obtained using deformation-potential theory (convenient formulas are given by Ji, et al. [8]) in combination with the model of van der Walle [9] for the distribution of the strain-induced shifts between the conduction and valence bands For the case of in-plane tensile strains, the effects occur with opposite sign to those of biaxial compression; this led to a novel approach to the realization of III-V-semiconductor-based 8 - 14 μm infrared detectors [10]. The (100) is the only orientation in which the piezoelectric fields generated by lattice distortions in III-V material cancel because of symmetry. Proper treatment of other orientations, especially the (111), require inclusion of strain-induced electric fields, which can lead to interesting optical effects [11].

Grown-in lattice strain also affects transport properties of strained-layers. Measurements [12] of carrier masses in (In,Ga)As/ (Al,Ga)As heterostructures used in GaAs-based strained-layer field-effect transistors indicate that the electron effective mass at the Fermi level improves with the incorporation of additional indium into the strained quantum-well channel, but at a substantially slower rate than the electron effective mass decreases with increasing In in bulk (In,Ga)As. Strain effects on p-type transport are dramatically more beneficial. Since compressive biaxial strain for (100)-oriented layers energetically favors the valence band with low effective masses for in-plane transport, high in-plane hole mobilities are obtained with an associated reduction in the valence-band density of states. Hole effective masses in p-type

strained-layer materials can approach electron effective masses over a wide range of sheet-carrier densities [13]. As hole densities in the quantum well increase, the Fermi level will be driven deeper into the valence band, and at high sheet carrier densities will begin to populate the heavy-mass band for in-plane transport. Since the separation between the light-hole and the heavy-hole valence bands are determined by lattice strain, the sheet carrier densities at which hole masses in strained layers saturate at their bulk values will depend strongly on built-in lattice mismatch.

Strain Enhancements for Electronic and Optoelectronic Devices

The first widespread application of strained-layer epitaxy exploited the dislocation-free epitaxy of lattice-mismatched materials. Confinement of carriers in the conducting channels of (Al,Ga)As/GaAs MOdulation-Doped, heterojunction, Field-Effect Transistors (MODFETs) is limited by the formation of DX-centers in the n-type (Al,Ga)As layer at Al mole fractions near 30%. While higher Al mole fractions would have been preferred, these defects led to transconductance degradation at cryogenic temperatures. Rather than increase the bandgap of the barrier, a more effective alternative was to apply lattice-mismatched (In,Ga)As layers to decrease the bandgap of the quantum-well channel compared to that of unstrained GaAs channels. This approach led to field-effect transistors with extrapolated maximum frequencies that exceeded 200 GHz [14]. Since, as described above, the electron effective mass at the Fermi level was not significantly enhanced by strain, the improvement of n-channel MODFET performance derives mainly from the dislocation-free application of narrower-bandgap materials for MODFET channels, a trend which continues in the use of higher-performance, higher In-mole-fraction (In,Ga)As strained-layers over InP substrates [15]. In contrast, strain-tailoring has found direct application to p-channel FETs for III-V complementary logic [16], where impressive device performance (1-mm gate-length FETs with transconductance exceeding 170 mS/mm) has been attributed to light-hole transport in the strained-layer.

Remarkably, most of the high-performance n-channel, strained-layer FETs are grown metastable [4], that is, with strained-layers thicker than allowed by thermodynamic limits. However, since these layers are not subjected to sufficient energy to nucleate dislocations during subsequent device fabrication or operation, they remain in their metastable configuration indefinitely. Intentionally strain-relieved (In,Ga)As layers have found widespread application as ohmic contacts to improve heterojunction bipolar performance [17], where the strain-relieving dislocations apparently act as sinks for minority as well as majority carriers. As expected, most other

strained-layer devices, especially those lasers that have demonstrated long operating lifetimes, do satisfy thermodynamic stability criteria. [18].

By far, the most impressive improvements brought about by strained-layer epitaxy has occurred in semiconductor lasers. The reduced density of states from the strain-split light-hole band eased the population-inversion condition, reduced intervalence-band absorption, and decreased Auger recombination rates [19]. A 40% reduction in laser threshold current densities has been measured compared to those of identical, unstrained lasers [20]. Strained-layers also increase laser modulation bandwidth [21], reduce the linewidth enhancement factor, and reduce laser chirp [22]. Additional device improvements can be expected as more groups begin to exploit the bandstructure engineering made possible by these novel materials .

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