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Optical and electrical properties of $Ge_{1-y}Sn_y$ and $Ge_{1-x-y}Si_xSn_y$ direct bandgap semiconductors grown on Si and Ge-buffered Si substrates

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Silicon has been the miracle material for electronic device and integrated circuit applications, but it is a very poor light emitting source due to its indirect bandgap nature. Therefore, it has been very desirable to develop Si- and Ge-based direct bandgap semiconductors to expand the functionalities of these materials well beyond electronics. Toward this end, an intensive research effort in crystal growth has been made in the fabrication of direct bandgap epitaxial $Ge_{1-y}Sn_y$ and $Ge_{1-x-y}Si_xSn_y$ alloys. Also, in order to determine their potential not only for use in new novel optoelectronic devices but also for the possible full integration with current Si-based electronic technologies, the unique optical and electrical properties of these alloys have been characterized. The epitaxial $Ge_{1-y}Sn_y$ (y=0-7.5%) and $Ge_{1-x-y}Si_xSn_y$ alloys grown on either Si or Ge-buffered Si substrates using the ultra-high vacuum chemical vapor deposition have been studied through temperature- (T-) dependent photoluminescence (PL) and Hall-effect measurements. From the $Ge_{1-y}Sn_y$ samples, the direct bandgap (ED) emission PL peak from the Γ-valley and the indirect bandgap (EID) emission PL peak from the L-valley conduction bands to the valence band were clearly observed at 125 and 175 K for most $Ge_{1-y}Sn_y$ samples. At 300 K, however, most $Ge_{1-y}Sn_y$ samples mainly exhibit predominant ED emission with very weak EID emission. Using these T-dependent PL spectra, transition energies of EID and ED were plotted as a function of Sn concentration, and the results show that the indirect-to-direct bandgap transition occurs at ~7% Sn for fully relaxed $Ge_{1-y}Sn_y$ samples at 125 and 175 K. This true indirect-to-direct bandgap cross-over of $Ge_{1-y}Sn_y$ might also take place at about the same Sn content at room temperature (RT). In addition, the optical properties of $Ge_{1-x-y}Si_xSn_y$ thin films grown on Ge-buffered Si were also characterized, and the RT PL spectra of the samples clearly illustrate their tunable optical emission depending on Sn and Si compositions. These ternary $Ge_{1-x-y}Si_xSn_y$ alloys have many advantages including independently tunable direct and indirect bandgaps and strain state which may be compressive, tensile, or relaxed. The T-dependent Hall-effect measurements of the epitaxial $Ge_{1-y}Sn_y$ and $Ge_{1-x-y}Si_xSn_y$ alloys show that as-grown samples exhibit mostly n-type conductivity with RT mobilities very comparable to those of bulk Ge materials, indicating excellent crystal quality. As a result of the successful fabrication of device quality epitaxial $Ge_{1-y}Sn_y$ and $Ge_{1-x-y}Si_xSn_y$ layers, the development of various new novel Si- and Ge-based infrared optoelectronic devices such as light emitting diodes, injection laser diodes, highly sensitive photodetectors, and advanced biological and chemical sensing devices has become possible. This talk will present state-of-the-art in the advancement of $Ge_{1-y}Sn_y$ and $Ge_{1-x-y}Si_xSn_y$ alloys including the first group-IV direct-bandgap semiconductors, extensive PL characterization and electrical properties of the materials over a wide compositional range. This information should be useful for the development of next-generation optoelectronic devices which can be fully integrated with Si technology on a single chip under complementary metal-oxide-semiconductor compatible conditions.