BIANCHO Executive Summary

The BIANCHO project aimed to develop photonic components designed to significantly reduce power consumption at the component and system level in advanced communication systems. The intrinsic losses in telecom lasers and optical amplifiers (SOAs) are due to Auger recombination. Incremental approaches to overcome these problems have reached their limits. Dilute bismide alloys have the possibility to achieve a situation in the near- and mid-infrared where the fundamental energy gap is less than the spin-orbit-splitting energy at the valence band maximum, $E_g < \Delta_{SO}$, leading to the elimination of the dominant CHSH Auger recombination process in the alloy. There is also evidence that their energy gap and that of dilute nitride alloys has lower temperature dependence than conventional III-V alloys. BIANCHO therefore set four challenging objectives, to demonstrate:

- 1.5 μm $GaAs_{1-x}Bi_x$ lasers (x > 12%) with a reduced Auger contribution to the threshold current, to achieve threshold current density per quantum well (QW) < 100 A/Cm^2 and T_0 > 200 K
- 1.5 μm $GaAs_{1-x}Bi_x$ semiconductor optical amplifiers with the reduced Auger current allowing to raise the maximum operation temperature from 40 ^oC to 95 ^oC
- Dilute bismide-nitride electro-absorption modulators (EAMs) where the band gap shift with temperature is reduced from 0.5 nm/^{o}C to 0.1 nm/^{o}C
- High-speed GaAs-based dilute bismide photodetectors for telecom and wider THz applications.

The BIANCHO Consortium recognises that the results achieved, although world-leading, are nevertheless below the expectations and target specifications outlined in the Description of Work. Nevertheless, BIANCHO achieved the ***first-ever*** electrically pumped semiconductor laser including a dilute bismide (GaAsBi) active region. This was also the first GaAsBi laser operating at room temperature and the first bismide quantum well laser. By carefully designing the growth conditions, we were able to form high-quality GaBiAs single-quantum-well lasers with a bismuth incorporation of 2.2%.

The challenge however in growing dilute bismide alloys is to incorporate sufficient Bi in the active region to reach the condition where $E_g < \Delta_{SO}$, which we showed occurs once x > ~10%. It is generally easier to incorporate a larger Bi fraction using MBE rather than MOVPE. We therefore grew laser structures where the GaAsBi active region was grown using MBE at FTMC, while the barrier and cladding layers were grown using MOVPE at Marburg. This allowed us to drive the Bi composition to x = 6% in a $GaAs_{1-x}Bi_x$ active region, the highest Bi composition reported to date in any working laser.

Having established laser action at x = 6%, major effort was devoted to the development of GaAsBi/GaAs QWs with higher Bi compositions. PL was obtained from samples with x ~9%, of comparable quality to that obtained from laser material with x ~6%. This strongly indicates that lasing should be possible at x ~9%, although we were not able to demonstrate lasing action at this composition. Room temperature PL was also obtained from a $GaAs_{1-x}Bi_x$/GaAs QW structure with x ~11.5%, confirming the potential for laser action to be extended to this composition and beyond.

Overall, the project succeeded to study several samples where $E_g < \Delta_{SO}$. Temperature-dependent optical measurements on structures close to the $E_g = \Delta_{SO}$ resonance provided the first evidence for Auger suppression once $\Delta_{SO} > E_g$. This was achieved in both GaAsBi/GaAs and InGaAsBi/InP test structures.

Detailed studies were also carried out of the temperature dependence of the energy gap in GaAsBi/GaAs, GaInNAs/InP and GaAsBiN/GaAs devices. Evidence for ~50% reduction in the temperature dependence of the energy gap was found in some samples. However further measurements showed a large (~30 meV) inhomogeneous broadening of the band edge transition, limiting the usefulness of these alloys for use in EAMs.

Prior to the BIANCHO project, research on bismide-based semiconductors had been primarily materials based, with little progress towards device realisation. Overall, our work drove forward the growth and optimisation of dilute bismide alloys, including demonstration of the first electrically pumped dilute bismide lasers, and the first lasers with x > 6%, although not yet Auger-free lasers. Without question, we have opened and provided Europe with a lead in this field. The exploitation activities of the project participants include the first commercially available dilute bismide alloys, with GaAsBi layers being sold for improved efficiency terahertz sources and detectors by FTMC spin-off Teravil. Further opportunities have been identified and are being pursued by the BIANCHO partners in areas including; photovoltaics, ultrafast systems, mid-infrared sensing and spintronics.

Overall our work lays strong foundations for enhancing European competitiveness in the global telecommunications and other identified markets and ultimately leading to new high technology jobs for Europeans, based on the development and application of uncooled telecom and related components with significantly reduced power consumption both at the component and system level.