QUANTIZED ACCUMULATION LAYER AT THE Bi/InAs INTERFACE

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1. Introduction

The electronic properties of low dimensional systems have long been at the frontier of condensed matter physics. The interface between some semiconductors can support a quasi two-dimensional electron gas (2DEG), in which the electrons move freely parallel to the interface, but are otherwise confined. Such 2DEGs have shown a multitude of fascinating fundamental phenomena, for instance the integer and the fractional quantum Hall effect or two-dimensional superconductivity. It is also of enormous technological importance and has promoted the use of low-dimensional structures in components such as lasers, thin film field effect transistors, optical modulators, etc.

A surface accumulation of electrons can be generated by applying a voltage, for example, in a metal-oxide-semiconductor system. However, interfaces where the accumulation is an inherent property of the material are of special interest. If unoccupied surface states are present, the bands will bend downward relative to the Fermi level leading to an accumulation of electrons at the surface. InAs surfaces and some of their interfaces also support a surface accumulation of electrons.

Bi is a potential candidate in applications in spintronics due to its strong spin-orbit coupling the results in a splitting of the valence band *6p*- orbital of about 1.5 eV [1]. Bi crystals have a higher electron density at the surface than in the bulk, due to a relaxation in the top layer and bi-layer buckled formation in the (111) direction [2, 3].

Here we present studies by the Angle Resolved Photoemission Spectroscopy (ARPES) on the Bi/InAs(111) interface. ARPES is a major technique to characterize the electronic structure of solids. It allows direct measurement of the electronic structure of a surface 2DEG.

2. Experimental

The experiments were performed at the I3 beamline, MAX-lab, the synchrotron radiation facility in Lund, Sweden. InAs(111)-B samples were cut from n-type single crystal wafers (Wafer Technology Ltd.) with a carrier concentration of 8.7×10^{16} cm^{-3}. In situ cleaning that consists of several cycles of argon-ion bombardment (E = 600 eV) followed by an annealing atabout 400 °C. The temperature was monitored with a optical pyrometer. Surface long-range order was verified by Low Energy Electron Diffraction (LEED). Bi was deposited from a resistively heated at room temperature. The pressure during evaporation was around 2×10^{-9} mbar. The thickness of the deposited layer was determined by a quartz crystal thickness monitor. The amount of deposited Bi is expressed in terms of monolayers (ML),where one monolayer is defined as the surface atomic density of unreconstructed InAs(111)(1x1)-B surface (8.14×10^{14} cm^{-2}). After the bismuth deposition, the surface was annealed at 300° C for 10 minutes.

Angle resolved photoemission spectra were measured along the $\overline{\Gamma}-\overline{M}$ directions in the Surface Brillouin Zone (SBZ). The samples were oriented azimuthally using LEED. The overall experimental resolution was 30 meV.

3. Theoretical background

Surface states (SS) and Charge Neutrality Level (CNL)

At an interface there exist two different periodicities, one ruled by the surface and the other by the bulk. Because the bulk and surface charge distribution is different, the charge-rebalanced should have to keep at the interface as a result of CNL outbreak [4].

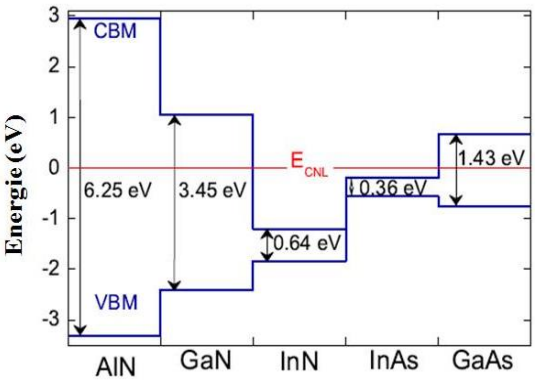

Fig. 1: *The conduction band minimum (CBM) and the valence band maximum (VBM) with respect to the charge neutrality level for AlN, GaN, InN, InAs and GaAs, and valence band offsets[5].*

If a semiconductor is not placed in an external electric field then it must be electrically neutral. The presence of unoccupied surface donor-like (occupied surface acceptor-like) states generates positively (negatively) charged surface.As soon as the surface is polar, it is unstable. The energy position of CNL(E_{CNL}) is located either above (if surface states SS are donor-like)or below the CBM (if they are acceptor-like), see Fig.1. Consequently, the net charge due to SS (Q_{SS}) have to be compensated by an equal opposite chargewithin the region near the surface, called the space charge region, Q_{SC}.

$$Q_{ss} = -Q_{sc} \tag{1}$$

In the case of an *n*-type, where the Fermi level (E_F)is below the CNL, the SS are positively charged. As a consequence, a charge accumulation layer is induced near the surface resulting in a downward band bending. Normally *n*-type III-V semiconductors show an electron depletion layer near the surface, except for InN and InAs, where a surface electron accumulation layer is seen.

To clarify the charge transfer mechanism we can refer to the *p-n* junction. It is accurately this mechanism which is implied at the interface and which creates a statically electrical field, induced by this Q_{SC}. From one side positively charged carriers are locally seated and at the other side those negatively charged, giving rise to an electrostatic potential. The charge compensation is reflected in the surface band bending curvature.

Band bending by Poisson's equation

The one potential V(z) describing the band bending in the space-charge region as a function of depth *z* below a semiconductor surface, must satisfy Poisson's equation (see e.g. [6]):

$$\frac{d^2V}{dz^2} = \frac{\rho}{\varepsilon(0)\varepsilon_0}\left[Na^- - Nd^+ - p(z) + n(z)\right] \tag{2}$$

$\varepsilon(0)$ being the static dielectric constant, Na^- (Nd^+)is the bulk acceptor (donor) density and *z* being the depth below a semiconductor surface. Obviously p(z) and n(z) depicted the carrier density VBM and CBM respectively.
The potential V(z) must satisfy the boundary conditions:

$$V(z) \to 0 \qquad \text{as} \quad z \to \infty \tag{3}$$

It means there is no band bending in the bulk of the semiconductor:

$$\frac{dV}{dz}\Big|_{z=0} = \frac{e}{\varepsilon(0)\varepsilon} n_{ss} \tag{4}$$

where n_{ss} represents the surface state density.
Two cases of potential V(z) evolution are possible: If V(z) < 0 then there will be an upward band bending and the space-charge zone will have a positive sign. In the second case, V(z) > 0 implies a downward band bending[6].

4. Results and discussion

Valence band photoemission results help us to check the 2DEG's density evolution after Bi has been deposited onto clean annealed InAs(111)B surface where the Bi atoms are acting as additional electron source [7].

a) b)

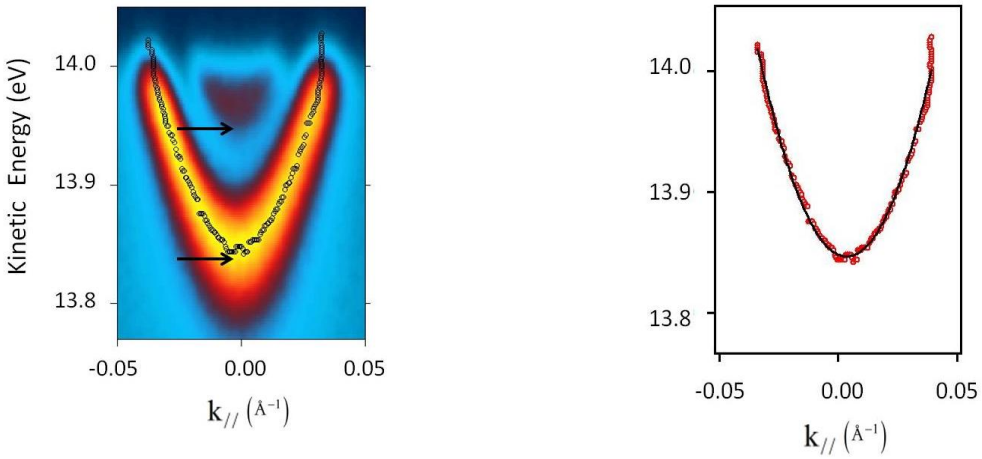

Fig.2: *a) ARPES result on Bi/InAs(111)B, arrows indicate sublevels; in black open circle stand for the measureb) parabolic fit, in red open circle stand for the measure and black line is the simulation; spectrum equation : E(k) = 121.97k² - 0.87k + 13.85. Effective mass value = 0.031m₀.*

The spectral intensity of a parabolic-like dispersion the accumulation layer is extremely high, comparable to the emission of bulk band states. This surface state was also observed on clean InAs surfaces [7-9]. Bi being a donor, its presence results in further downward band bending allowing observation of more sublevels than on bare InAs surface[9]. The surface state contains at least 2 sublevels (Fig.2a).
We simulated by experimental spectrum and obtained the effective mass value for the first sublevel of m^*=0.031m_e(Fig.2b). The effective mass of valence electrons in Bi crystal (m^* = 0.003 m_e) is much smaller than in InAs (m^* = 0.023 m_e)[10].Comparing the dispersions on the Bi/InAs(111)-B and on the clean InAs(111) surfaces extracted from [9], we can conclude that the presence of Bi atoms on the surface reduces the effective mass of the 2DEG.

5. Conclusion

The small effective electron mass in bismuth makes it an interesting candidate for electron confinement. This may offer a potential for density-controlled band engineering schemes in electronic devices.

Acknowledgements

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6. References

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