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Polyatomic Ions from Liquid Metal Ion Source driven High Current Ion Implanter

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Abstract: High current liquid metal ion sources are well known and found their first application as field emission electric propulsion (FEEP) thrusters in space technology. The aim of this work is the adaption of such kind of sources in broad ion beam technology.

Surface patterning based on self-organized nano-structures on e.g. semiconductor materials formed by heavy mono - or polyatomic ion irradiation from liquid metal (alloy) ion sources (LMAIS) is a very promising technique. LMAIS are nearly the only type of sources delivering polyatomic ions from about half of the periodic table elements. To overcome the lack of only very small treated areas by applying a focused ion beam (FIB) equipped with such sources, the technology taken from space propulsion systems was transferred into a large single-end ion implanter. The main component is an ion beam injector based on high current LMAIS combined with suited ion optics allocating ion currents in the µA range in a nearly parallel beam of a few mm in diameter. The mass selection of the needed ion species can be performed either by an ExB mass separator (Wien filter) and/or an existing dipole magnet of the ion implanter itself.

Different types of LMAIS (needle, porous emitter, capillary) are presented and characterized. The ion beam injector design is specified as well as the implementation of this module into a 200 kV high current ion implanter (Danfysik model 1090) operate at the HZDR Ion Beam Center (IBC). Finally, the obtained results of large area surface modification of Ge using polyatomic Bi_2^+ ions at room temperature from a GaBi capillary LMAIS will be presented and discussed.

Keywords: Polyatomic ions, liquid metal alloy ion source, implanter, surface pattern

I. INTRODUCTION

The investigation and development of liquid metal (alloy) ion sources (LMAIS) has a long history [1] and culminates about 60 years ago in the idea to use it as a heavy particle propulsion system for space thrusters [2]. Later on, it was found that this type of source is an ideal candidate for focused ion beam (FIB) systems [3]. The capability of LMAIS to emit a broad variety of ions from nearly half of the periodic table including molecular ions or small clusters, consisting of a few atoms and different charge stages render them unique for special applications. LMAIS are characterized by a high brightness of about 10^6 A/cm^2 sr, low energy spread of some eV and a compact design which lends them for FIB systems [4,5] and for further appreciation as field emission electric propulsion (FEEP) thrusters in space technology as well [6,7].

A modern implementation is dedicated to the emission of heavy metallic polyatomic ions – a speciality of LMAIS. With Bi or Au polyatomic ions in the energy range of some 10 keV, regular self-organized hexagonal dot structures were obtained after room temperature irradiation of Ge at normal incidence using a mass-separated FIB instrument [8]. The patterning is induced by the enormous energy deposition of the heavy projectiles due to the simultaneous impact of several atoms at the same place. However, due to the low available currents at FIBs, this technique is restricted to only small (~µm) areas [9]. Consequently, an ion injector based on a high-current LMAIS for broad beam ion implantation system is the aim of this work, i.e. to process larger areas which is the unique feature of this development.

II. EXPERIMENTAL

A. High current ion sources

Different types of field emitters were tested and characterized for a high permanent ion current of more than 100 µA. Three kinds of emitters were prepared and investigated, among them a classical hairpin needle emitter made from 250 µm tungsten wire. The achievable ion beam current from this type of emitter is limited due to the material replenishment mechanism (materials can only flow in a thin film on the needle surface to the apex). A typical I-V curve is shown in Fig. 1a. Other high current LMIS emitters and their characteristics are shown in Figs. 1b and 1c for comparison. (i) Emitters with electrochemically etched porous tungsten needles (Fig. 1b) with a tip diameter less than 10 µm have been developed in space engineering as field emission electric propulsion thrusters[6]. Due to a liquid metal flux inside and outside of the needle currents of above 100 µA are reachable for long-term operation. For higher ion currents and long operation times, erosion at the needle tip was observed. (ii) Furthermore, emitters with tantalum capillaries (Fig. 1c) with an inner diameter of 50 µm and an outer diameter of 150 µm have been developed which showed an excellent and stable emission behavior up to about 500 µA. As the Taylor cone forms on the outer diameter of the capillary, the starting voltage of the capillary emitter increases. The slope of the capillary current-voltage characteristics is very steep because of the large base radius of the Taylor cone. For the first experiments, Ga has been used as source material followed by a $Ga_{38}Bi_{62}$ alloy [10] for the production of heavy mono – and polyatomic Bi ions.

Both latter emitter types, shown in Fig. 1b and 1c were combined with a cylindrical reservoir with a volume of about 150 mm^3 to allow long operation time with high ion currents. The capacity of liquid metal inside these reservoirs is more than 50 times higher compared to classical Ga-LMIS operating in low-current mode.

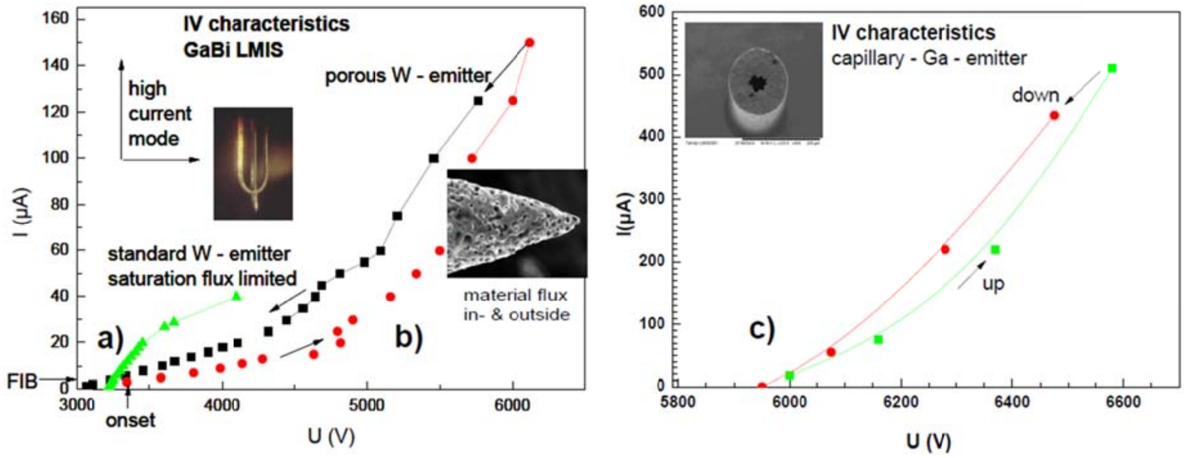

Fig. 1: (Color online) The I-V curve describes the behavior of LMAIS depending on the applied extraction field for three types ion emitters. a) standard hairpin needle emitter, (triangles), b) porous W-emitter, c) capillary Ta emitter. The insets show pictures of the certain ion emitters.

B. Ion injector design

To overcome the lack of the high ion emission half angle from the protrusion of the Taylor cone (~ 50° [3]) from LMIS and to bring the majority of the emitted ions into a compact beam a set of lens electrodes were placed close to the extractor following ion optical calculations using SIMION code. The injector-module is thus separated in two units: - The LM(A)IS unit consists of emitter and extractor electrodes and a heater to liquefy the chosen metal or alloy. Applying indirect heating to an Al_2O_3 vessel reservoir surrounded by constantan wires separates the high voltage (HV) potential for ion emission from the heating current, which enables the usage of standard laboratory power supplies. The temperature can be controlled by a k-type thermocouple (TC). All electrical feed throughs for HV, heater and TC are located on the rear side of the module. The modular design enables a fast emitter change and usage of different emission materials. To obtain a stable emission the distance between emitter and extractor was adjusted to about 0.7 mm. Extractor apertures with a diameter between 1 and 3 mm were tested. For different sources, the emission onset was in the range of 5 – 8 kV. An additional voltage of about +50 V on the grounded extractor suppresses strong electron emission in the case of high current operation. Without secondary electrons would be accelerated to the tip and the emission becomes unstable such that the source begins to oscillate from on- to off-status. The strong increasing beam divergence at very high emission currents caused by the Boersch effect (Coulomb interaction) [11,12] can be critical as well a broadening of the angular distribution of the ion emission from the source [13] leading to deposition on the lens electrodes and insulators.

The second part of the injector-module is the beam formation unit, which consists of an asymmetric Einzel-lens. Polyetheretherketone (PEEK) for electrical insulation and labyrinths due to scattered ions or metal vapor have been considered to allow long-term operation. Because of extensive ion optical calculations, the high voltages on the first and second electrode of the Einzel-lens differ only some ten volts from the emitter potential in order to get a small beam diameter. A third electrode of the Einzel-lens is grounded. A cross-sectional view of the source and lens design (diameter ~ 80 mm) is presented in Fig. 2a. The resulting beam profile for a Ga LMIS (I_{em} = 90 µA) measured using the knife edge method in front of the Faraday cup (FC) at a distance of 50 cm is shown in Fig. 2b. The derivative of the transmission curve delivers the beam profile.

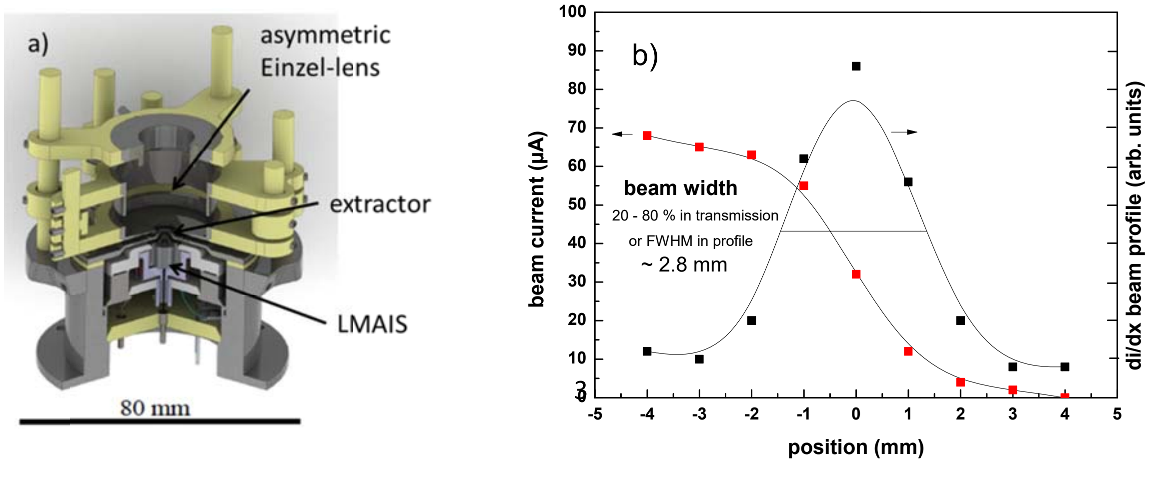

Fig. 2: (Color online) (a) Cross-sectional view of the source module with an asymmetric Einzel-lens, (b) the resulting current transmission profile for a Ga LMIS (I_{em} = 90 μA) measured using the knife edge method in front of a Faraday cup at a distance of 50 cm. The derivative of the transmission curve (red) delivers the beam profile.

C. Implementation of the injector module to an implanter

The injector module was implemented and tested on two positions on a Danfysik High Current Implanter (model 1090) depicted schematically in Fig. 3 [14].The first attempt has been the linear beam line through the analyzing magnet, which was switched off, marked as Exp1 in Fig.3. The source module has to be accurately adjusted with respect to the ion optical axis of the machine. Due to the length of about 2 m up to the acceleration tube and a diameter of only 1 inch, the transmitted ion current was quite low. So a second position was evaluated and used by removing a slit device directly very close to the acceleration tube, see Exp 2 in Fig. 3. Here, the acceptance of the further ion optics was essential: higher currents in the μA range could be achieved in the Faraday cup introduced in front of the target plane in beam line 1. It should be mentioned that in both cases of injector implementation, the LMAIS has to be set on the acceleration potential of the implanter concerning to the construction scheme of the machine so that the source power supply had to be controlled via a light guide connection. Typical currents for different ion species from the two source positions (Exp1 and Exp2) and different acceleration energies are plotted in Fig. 4. Additionally, the values are compared with usual currents obtained in a mass separated FIB system using a GaBi LMAIS[15]. The cup current corresponding to double charged ion species is corrected in the plot. The mass separation can be either accomplished by an integrated ExB mass filter in the injector or like in the present experiments by using the common application of the switching magnet of the implanter. At energies of about 20 keV polyatomic ions up to 1045 amu (Bi_5) can be separated for the application, as shown in Fig. 4. Due to the cluster size in this case the fluence is fivefold.

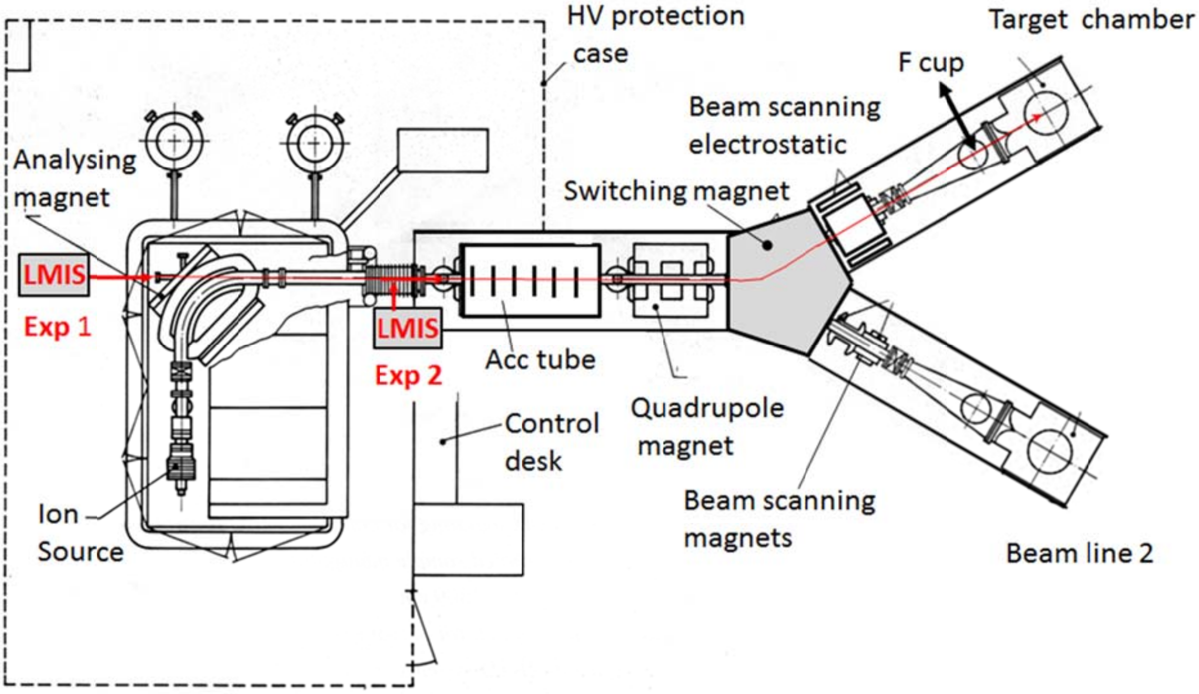

Fig. 3: (Color online) LMAIS injector module positions implemented in a Danfysik model 1090 high current ion implanter (schematic)[14].

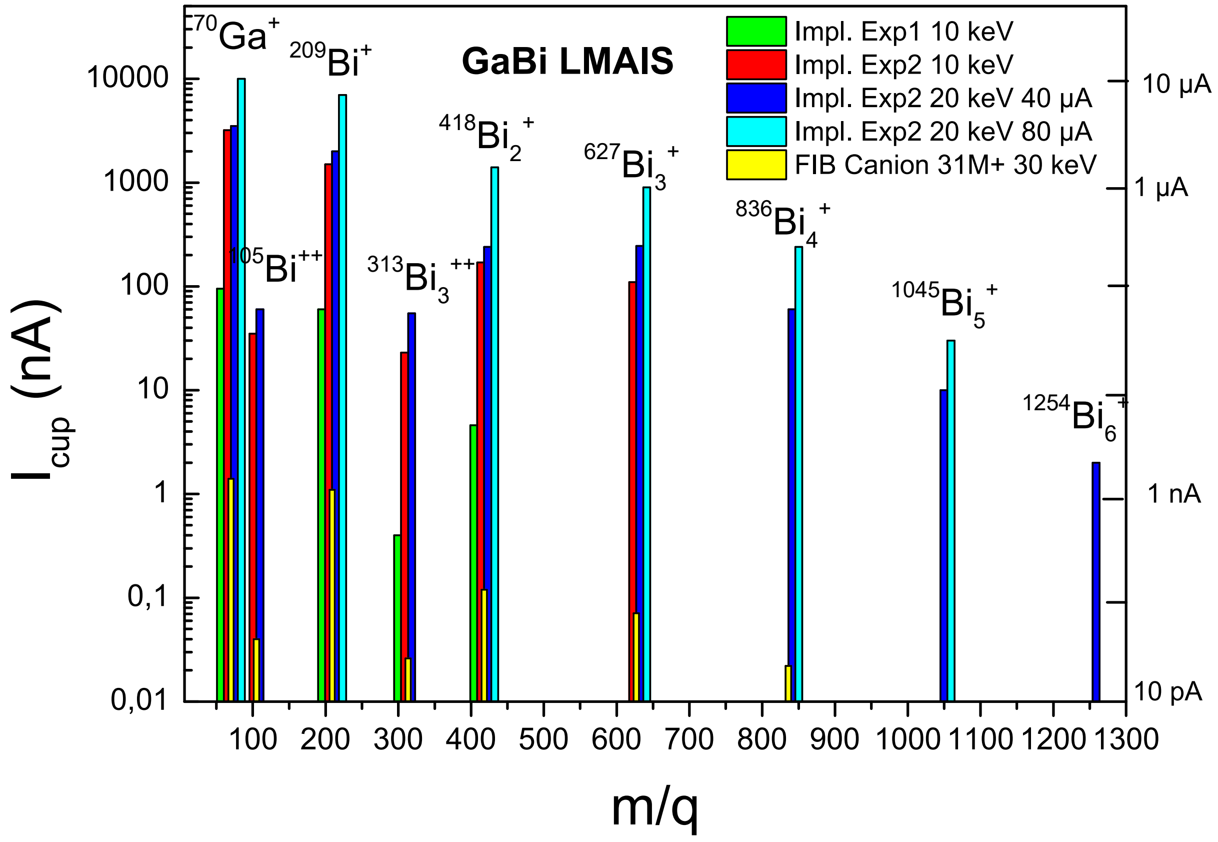

Fig. 4: (Color online) Obtained target currents for different ion species in the ion implanter from two different source positions (Exp1 and Exp2) and different acceleration energies and two emission currents for 20 keV, compared with usual currents of a mass separated FIB system[15]. The cup current corresponding to doubly charged ion species is corrected in the plot.

IV. RESULTS AND DISCUSSION

A. Ion beam performance

To control the performance of the ion beam for all species of interest, the optimized current was measured in an FC at the end of the beam line under conditions of a further use. The quality of the spot was imaged and analyzed using a standing beam on a Ge-target. The stability of the system and also the source was measured in the same manner over approximately two hours.

As an example, the beam current of Bi_2^+ ions on the target of the 1090 implanter (LMAIS position Exp2) as a function of the emission current at an ion beam energy of 20 keV is presented in Fig. 5. The ion target current is also increasing with ion beam energy up to about 30 keV for $Bi_2^+$and is then decreasing due to the performance of the internal quadrupole magnet.

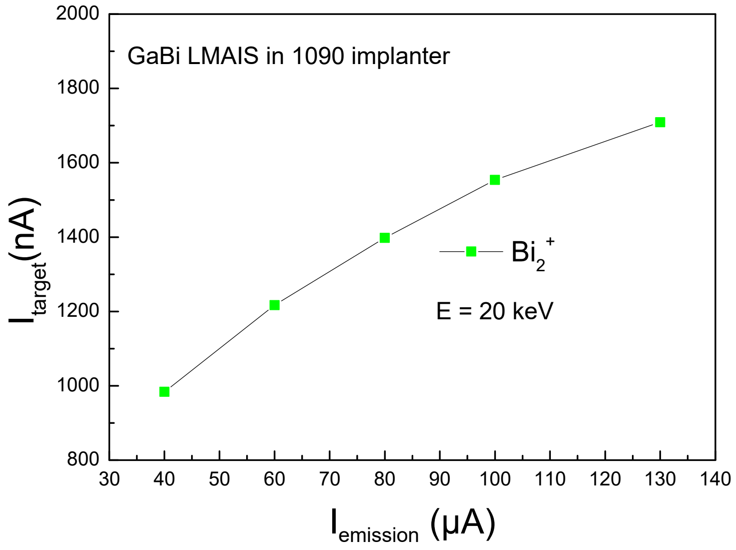

Fig. 5: (Color online) Beam current of binary Bi_2^+ ions on target of the ion implanter from a GaBi LMAIS (position Exp2) as a function of the emission current at an ion beam energy of 20 keV.

B. Applications

In first experiments the formation of self-organized hexagonal dot pattern on a Ge surface, found after FIB irradiation of polyatomic Bi ions[8] was performed on a larger area by the implanter. Using the same energy of 30 keV and the same ion species Bi_2^+ for the irradiation at room temperature in normal incidence, the patterns are compared with the FIB results depicted in Fig. 6, which shows nearly the same quality of surface patterning under ion treatment.
The FIB modified area of the surface was only 5x5 μm² in size, now with the implanter areas of mm² are attainable which gives access to new technological applications.

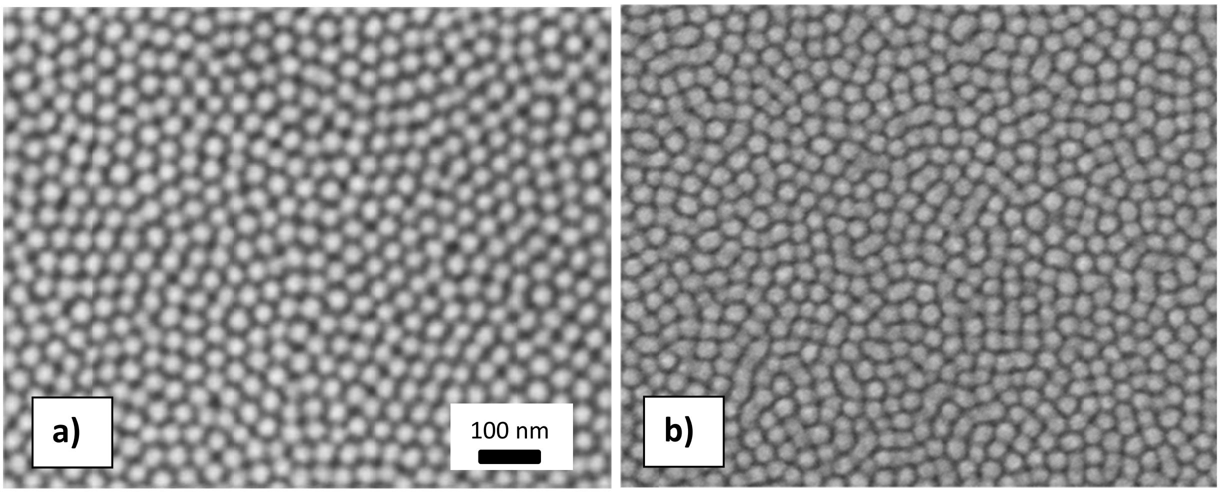

Fig. 6: (Color online) Scanning electron micrographs from hexagonal dot pattern on Ge made by 30 keV Bi_2^+ irradiation at normal incidence at RT, (a) from an ion implanter (Danfysik model 1090) and (b) from a mass separated FIB system (Canion31M+, Orsay Physics)[8].

V. SUMMARY AND OUTLOOK

High current reservoir LMAISs based on porous tungsten needles or tantalum capillaries combined with suited ion optics as ion injector for single-end ion accelerators (implanters) delivering µA currents open access to new application fields. The developed LMAIS - module with an additional beam formation unit provides high currents of mono- or polyatomic ions of metallic or semiconducting elements. A mass separation system (Wien filter) or system integrated magnets can be used to select the desired ions out of the nearly parallel ion beam having a diameter of 2-3 mm. In first investigations of a high current GaBi LMAIS injector module in a conventional implanter, heavy mono - and polyatomic mass separated ion species in the µA range could be used for large area surface modification in the same quality known from FIB experiments.

New experiments, like heavy ion interaction on 2D materials, study of single impacts of high mass projectiles or effective cluster deposition after de-acceleration of the ion beam are possible due to the unique feature of the combination of a high current source for heavy polyatomic ions and a single end ion accelerator such as an ion implanter.

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