INEXPENSIVE RECEIVER COMPONENTS FOR MILLIMETER AND SUBMILLIMETER WAVELENGTHS

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Abstract

In recent years there has been excellent progress in the development of millimeter and submillimeter wavelength components such as mixers and multipliers. Particularly, SIS mixers have yielded sensitivity near the quantum limit at frequencies approaching 1 THz and hot-electron bolometric mixers now promise similar performance above 1 THz. However, for many applications the cost of building and maintaining cryogenic systems is prohibitive. In such cases, GaAs Schottky diode technology remains a very attractive option, provided the sensitivity requirement is not so great, particularly now that planar (whiskerless) diodes are yielding good performance. However, even in the case of Schottky mixers and multipliers, the cost of machining the waveguide blocks can be prohibitive, particularly at THz frequencies and/or when array applications are considered. In this paper we summarize two techniques which allow low cost manufacturing of millimeter and submillimeter wavelength components.

I. BACKGROUND

The most successful millimeter and submillimeter wavelength components, such as oscillators, multipliers and mixers, generally use traditional metal blocks which are fabricated by standard machining techniques. These components yield excellent coupling to the electronic circuit elements, are highly reliable, and are relatively straight-forward to design. However, the cost of fabricating such blocks can be prohibitively high, particularly as the frequency is increased and/or arrays of components are considered.

Typical components are formed by the so-called "split-block" technique, where the circuit structures are formed on a single face of two (or more) metal blocks which are then pieced together to form the complete components. This process has two primary advantages, the machining is, in principle, straight forward and the circuit components, such as filters, coupling structures and diodes, can be easily placed into the block during assembly. Although this process has been extended to the THz frequency region [1], and has lead to the development of many successful systems, the cost of the required machining tools and the expertise required greatly increase the expense and fabrication time of such components. In fact, the high cost of machining such components is perhaps the primary factor which limits the extension of millimeter-wave technology to large scale applications such as collision avoidance radars, personal communications, aircraft landing systems, and contraband detection.

We are developing two methods which have the potential to greatly reduce the manufacturing costs of millimeter and submillimeter-wave components. The first is a method of Mastering, Molding and Casting by which many inexpensive copies are produced from an initial "Master" by a process of molding and casting. Although the formation of the original Master will often be done by standard machining techniques, the final casting of many components will greatly reduce the per piece cost. The second method allows the formation of high quality horns, waveguides and channels directly in a silicon wafer by novel micromachining techniques.

II. COMPONENT FABRICATION BY MASTERING, MOLDING AND CASTING

Molding and casting has a long and successful history of fabricating inexpensive components for myriad applications. The basic process involves three major steps, as is depicted in Fig. 1.

1) The fabrication of an original master, which has all of the dimensional characteristics of the desired component.
2) The formation of a mold, or molds, from the master, which maintain all of the essential features but in a "negative polarity".
3) The final production of many parts, geometrically identical to the master, from the molds through a casting process.

However, the fabrication of millimeter and submillimeter wavelength components by casting has not, to our knowledge, previously been reported. The demand for extremely small features and precise component alignment requires special techniques and materials. The new Mastering, Molding and Casting (MMC) process which we propose[1], incorporates several novel techniques and each of the fundamental process steps is optimized for high frequency waveguide component fabrication. This MMC process is not one of merely replicating an existing part, but rather it is an integrated manufacturing technology.

The design of the master is quite different from the design of standard machined waveguide blocks since the geometry must be optimized for the subsequent molding and casting process. The fabrication of the master is naturally a critical step, and is in most regards as difficult and costly as the fabrication of a standard component. However, in forming the master we have the advantage that its mechanical, electrical, thermal and other properties need not be optimized for use as a final component. For example, it need not be electrically conductive or suitable for temperature cycling. Rather the material used for the master can be selected for its machinability and suitability as a master component. Furthermore, great resources can be

1. Provisional patent applied for March 26, 1997, "Mastering, Molding and Casting (MMC) Technology for High Precision, Fabrication of Millimeter and Submillimeter Wavelength Hollow Waveguides, Channels, Horns and Assemblies."

expended on the master since it will be used to fabricate many final parts. Masters can be made with composite structures and can be formed with a combination of additive and subtractive methods. The cost of the master is spread over the many final parts that are cast, provided, of course, that a market exists for a sufficient number of components.

Only a few commercially available materials are suitable for the formation of the mold in this process. The primary concerns are maintenance of the critical dimensions, ruggedness of the mold, and excellent release properties. We have used a silicone material for the mold and we have also developed a unique mold formation fixture and techniques which secure the master and the mold resin, reinforce the mold for excellent dimensional control and facilitate efficient mold fabrication. Fig. 2 shows one of the silicone molds as well as a master and casting of a test structure consisting of a 585 GHz waveguide section and two diagonal horns. As can be seen from the figure, the mold was formed in a metal ring to give it structural reinforcement and make it easier to handle.

In the casting process we have used a specially selected polyurethane material although other casting resins such as epoxies may be suitable. The mechanical and thermal properties of this casting resin are very critical. Essentially, the polyurethane is poured into the mold, cured and then removed. However, care must be taken to eliminate air bubbles at the surface of the casting which can create pits in the final waveguides or horns. Several techniques have been developed to form the back side of the casting without further machining. Also, such things as the curing process and the removal of the casting from the mold must be carefully planned to avoid damage to the mold and/or the casting.

In order to complete the fabrication process we have coated our cast components with gold in a sputter deposition system and then electroplated additional gold to a thickness of a few microns. At this point we have tested the dimensional accuracy of the castings. Fig. 3 shows scanning electron micrographs of a small portion of a master and a casting. We have also assembled cast components by the split block technique. Although we have noticed a small but appreciable "bowing" of the castings, we have found that with a small amount of pressure the components can be brought into intimate contact along the entire contact surface. This problem is now being addressed through improvements of our process and we do not expect it to cause appreciable difficulty. Finally, we have immersed the completed components into liquid nitrogen. Upon warming we see no noticeable change, either in the dimensional quality, or the final gold surface.

We have successfully used this MMC process to fabricate a complete 585 GHz mixer of the design described by Hesler [2]. This involved the machining of a master for each half of the block, the formation of molds, the casting and metalization of the block halves, and the installation of the quartz microstrip circuit with the planar Schottky diode as well as the SMA connector for dc bias and IF output. The measured beam pattern of the cast horn was as expected from the design and very comparable to that achieved with a traditional block. With a non-optimized diode, a mixer noise temperature of 12,000K (DSB) was measured. Although this is about a factor of five worse than our best result at this frequency, it is better than we had previously achieved with this particular diode design in a conventional machined mixer block. Further measurements with optimized diodes are now in progress.

III. THE FABRICATION OF COMPONENTS BY MICROMACHINING

In general terms, the fabrication of components by micromachining involves the use of techniques and processes developed by the microelectronics industry for the fabrication of complex integrated circuits. Through the use of micromachining we hope to be able to simultaneously fabricate many complete split block components on large silicon wafers. Although this general idea is not new, previous attempts have suffered from significant drawbacks. For example, Rebeiz [3] has fabricated mixer assemblies based on micromachined horns and detector elements integrated onto silicon nitride membranes. However, since his horns were formed directly on the (111) crystal faces of silicon, their flare angle was roughly seventy degrees, as determined by the crystal planes. This large flare angle is not conducive to the formation of the excellent beam patterns required for most applications. Other groups have tried to develop standard components using photoresist formers [4], upon which waveguides could be formed. These efforts suffer from two difficulties, first the photoresists available were not thick enough to form the relatively large features needed at millimeter wavelengths and second the resists were difficult to remove from within the newly formed waveguide channel. Also, the problem of forming excellent horn antennas on the silicon wafer was not solved.

In our micromachining work we have solved these problems by inventing a new way to micromachine horns in silicon crystals and using a new photoresist material which easily achieves the dimensions required.[2] Our process consists of two basic steps, the etching of an initial horn structure directly into the silicon substrate and the subsequent use of the EPON SU-8 [5] photoresist to complete the horn and form the necessary waveguides, channels and other physical features of the block.

Etching of a Horn with Small Flare Angle

Our method of etching the horn into the silicon wafer results in a shape that is very similar to a traditional diagonal horn, except that the angles of the aperture are not ninety degrees, but rather 70 and 110 degrees. The horn is formed by etching into the silicon wafer with a selective etch through a silicon dioxide mask. The flare angle of the horn is determined by an easily controlled angle in the original SiO2 etch mask. An SEM photo of such an etched half-horn is shown in Fig. 4. Note that the wafer has been diced to open the aperture of the horn and that the silicon etch was timed to yield a flat (100) surface on the bottom of the aperture, rather than a full diagonal horn.

Formation of Integrated Waveguides and Channels

To form the desired integrated waveguides and channels a layer of the extra thick resist [5] is spun onto the silicon wafer. This resist fills the horn and forms a planarized surface above the silicon wafer. This resist can be as thick as 500 microns, and multiple layers can be used to

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2 Provisional patents applied March 26, 1997, "A Preferential Crystal Etching Technique for the Formation of Millimeter and Submillimeter Wavelength Horn Antennas," and "Integration of Hollow Waveguides, Channels and Horns by Lithographic and Etching Techniques."

achieve even greater thickness. The resist is then exposed through a mask that defines the horn and the waveguide channels. Before development, a second layer of resist is added. It is exposed in the shape of the horn, waveguide and also the microstrip channel. Both layers of resist can then be exposed simultaneously to clear the volume of the horn, waveguide and channel. The remaining resist is subsequently cured and the entire wafer is metalized, yielding the final split block mixer as shown in Fig. 4.

We also use a third layer of the resist to form alignment pins to aid the assembly of the mixer block. To date we have successfully assembled a complete mixer, but it has not yet survived a complete mixer test. Although we believe the structure can be made to be quite robust, we have not yet completely worked out the details of the alignment pins. We have also found that the materials used do not survive cooling to 77K in a liquid nitrogen bath. We are presently working to build and test our first micromachined mixer and exploring methods to solve the cryogenic cooling problems.

IV. SUMMARY

We are developing two techniques that will allow the inexpensive fabrication of mixer, multiplier and oscillator blocks. The first uses a novel Mastering, Molding and Casting (MMC) technique to form many inexpensive split blocks from a specially designed master. To date we have demonstrated the process by building a complete 585 GHz Schottky mixer of the design described by Hesler [2]. The resulting product is of high quality and very robust. Although we have made preliminary noise temperature measurements, we have not yet tested the mixer with a high quality Schottky diode.

The second technique involves a novel micromachining process. In this process we have invented a method to micromachine high quality horns with small flare angles which are aligned in the plane of the silicon wafer. Although the horn shape is still dictated by the silicon crystal planes, we can achieve small flare angles simply by controlling the shape of a simple photolithography mask. Also, the beam shape can be further adjusted by controlling the silicon etch time and the thickness of the layers used to form the waveguides and channels of the mixer. Through the use of the new photoresist, we have successfully integrated high quality rectangular waveguides and microstrip channels with the horns. The resulting structure is an accurate reproduction of Hesler's 585 GHz mixer. To date, we have not completed a mixer assembly, due to minor problems with the integrated alignment pins. When this process is perfected we expect to be able to fabricate dozens of mixers simultaneously on a single silicon wafer.

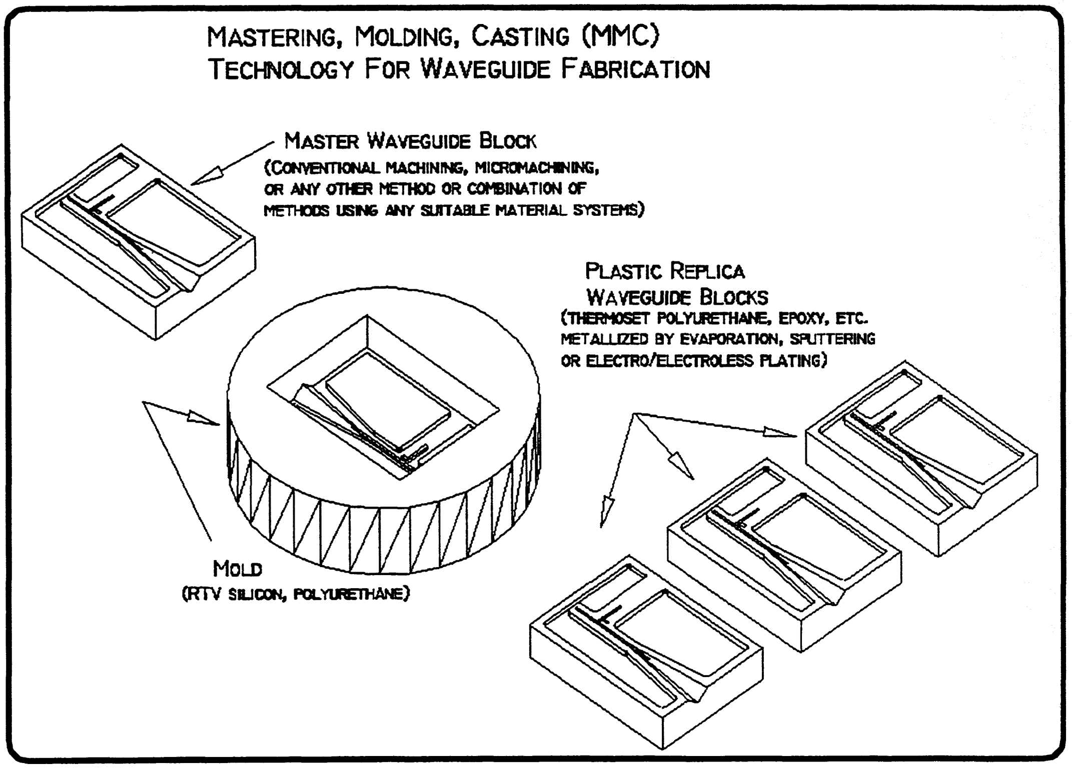

Figure 1. The basic principle of fabricating split-block components by the method of Mastering, Molding and Casting (MMC).

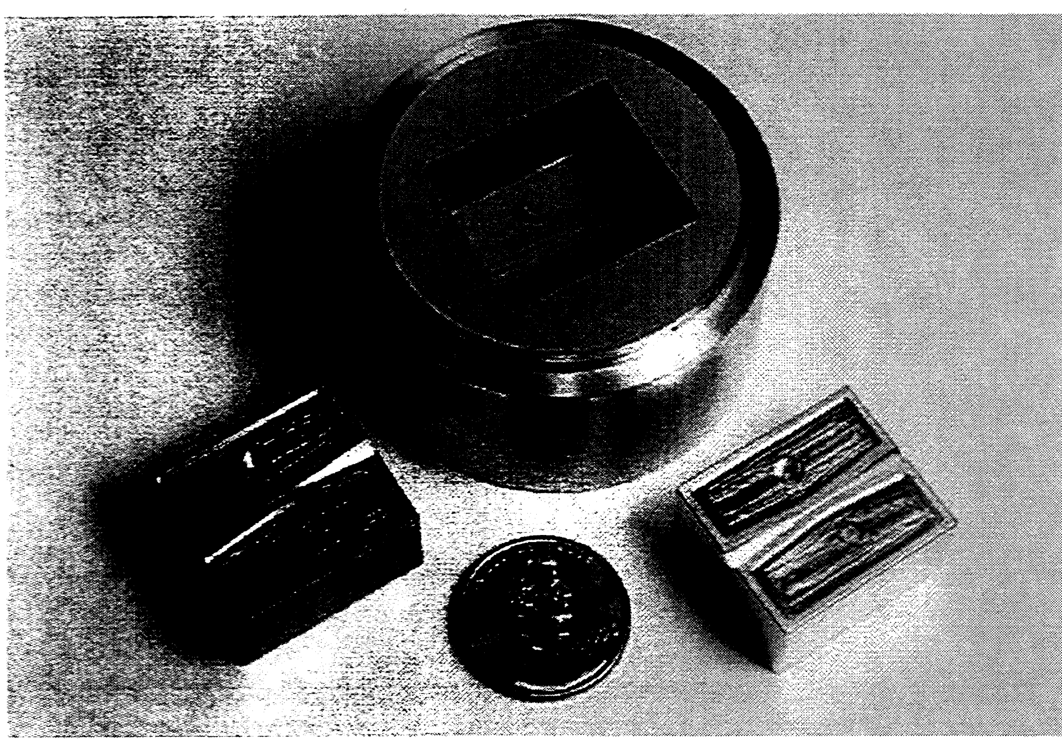

Figure 2. A photograph of a master (left), the silicone mold and a gold coated casting (right). The circuit is a 585 GHz waveguide and two diagonal horns.

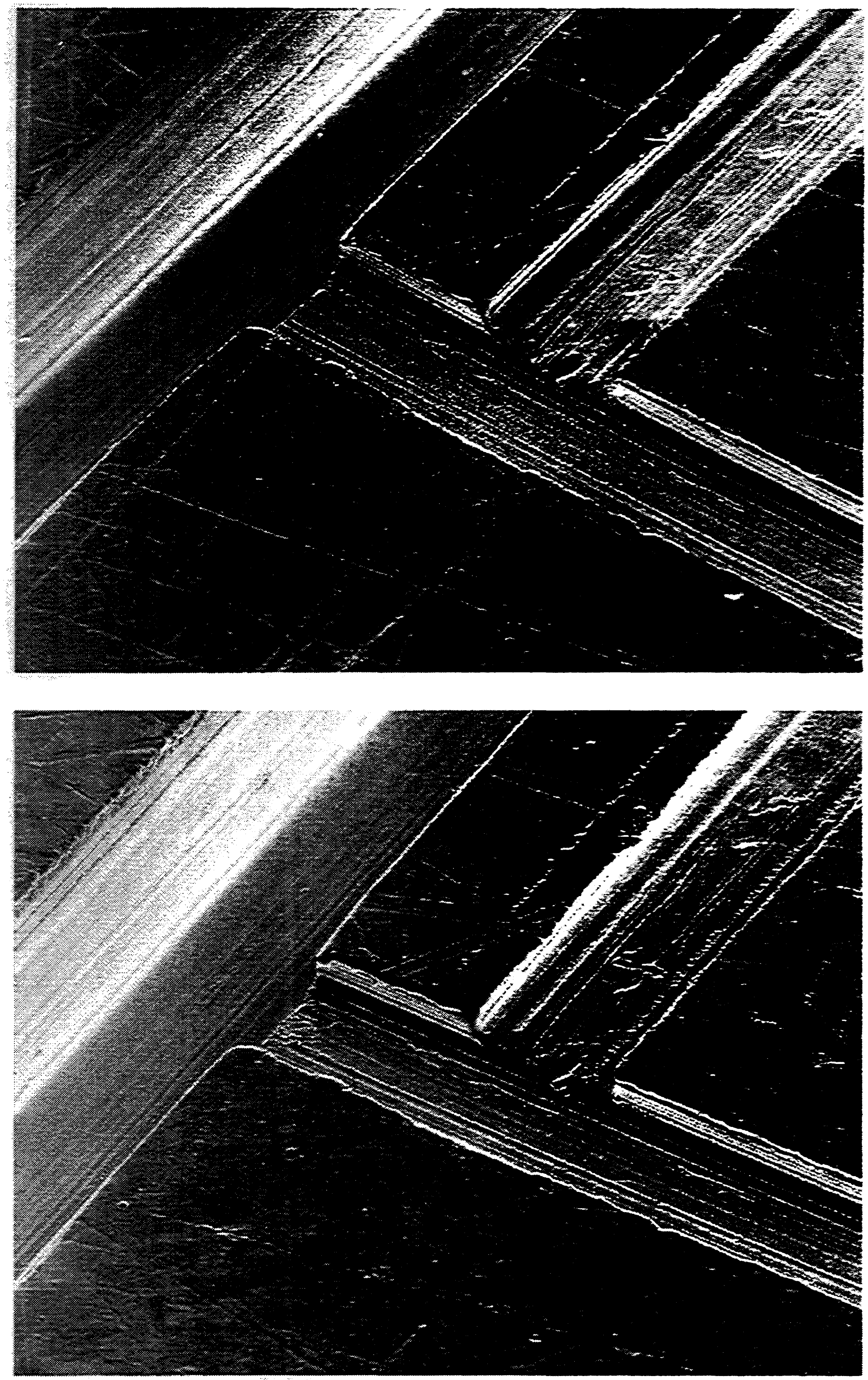

Figure 3. A SEM comparison of the surface of the 585 GHz mixer block master (top) and the metalized casting (bottom). The casting accurately reproduces the waveguide channels. The fine machine marks are reproduced but are partially filled in by thick plated gold.

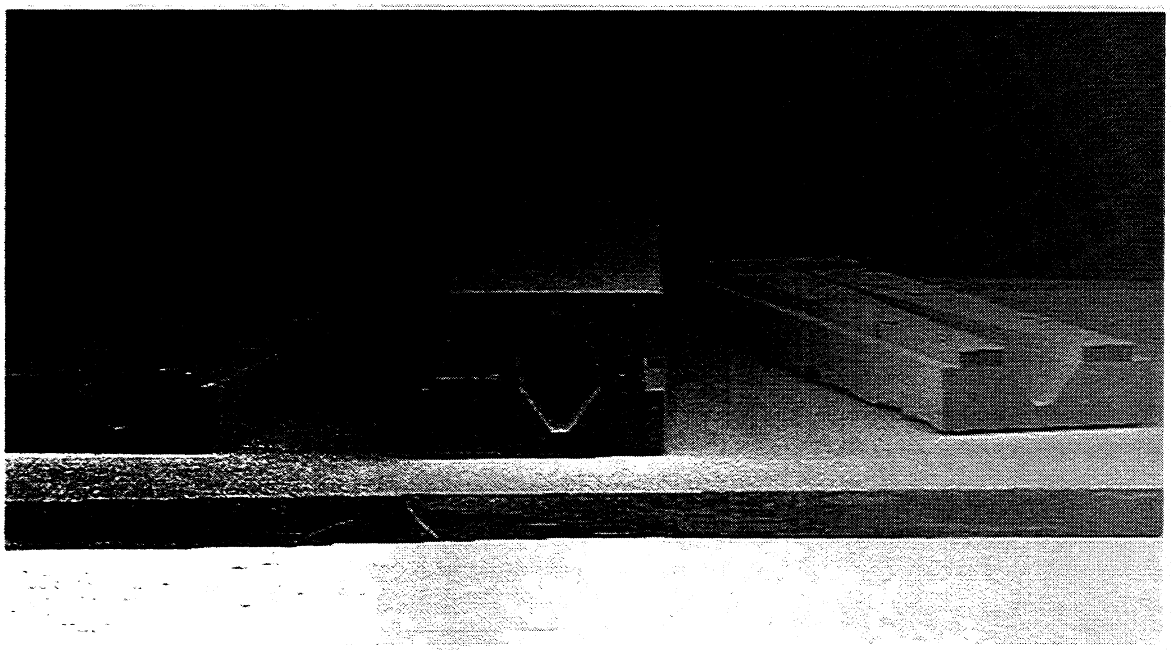

Figure 4. A SEM photo of an assembled 585 GHz micromachined mixer and two half blocks. Note the narrow taper of the integrated horn.

ACKNOWLEDGEMENT

The development of the MMC and micromachined components has been supported by the Army Research Laboratory under the Microelectronics Research Collaborative Program (UMd subcontract Q281601). The testing of the components was supported by a grant from the US Army National Ground Intelligence Center (DAHC90-91-C-0030).

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