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Computer Processing of the Output Optical Image of a Focal Plane Array of Uncooled Bimaterial IR-detectors by Method of Feature-oriented Scanning[1]

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Abstract—Application of the feature-oriented scanning (FOS) method intended for computer processing of the output optical image of an uncooled infrared focal plane array (FPA) of 32×32 elements is described. The FPA sensing elements are micromechanical bimaterial infrared (IR) detectors. The FPA under consideration is a microoptomechanical system (MOMS). Reading out the FPA optical image in visible spectral region is carried out by means of an optical profiler (interference microscope). The suggested method allows to exclude points from the output optical image, which do not carry useful information about the imaged IR-object, as well as to take into account artefacts introduced by the reading profiler. The method is suitable for determination of an array of correcting factors eliminating a non-uniform response of the FPA bimaterial detectors on input IR-radiation. The method can also be applied to automatic characterization of experimental MOMSs and for a spot-check outgoing inspection of commercial MOMSs.

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1. INTRODUCTION

Today, uncooled micromechanical bimaterial infrared (IR) detectors are a rapidly developing approach [1, 2]. The focal plane array (FPA) M3-50 consisting of 32×32 uncooled micromechanical bimaterial IR-detectors was designed and fabricated at the Moscow Institute of Electronic Technology [3]. The FPA is a microoptomechanical system (MOMS), where reading out of an IR-image is carried out by an optical method. The FPA is intended for acquiring thermal images in 8–14 μm range.

The operation principle of the FPA sensing element (see Fig. 1a) is based on the thermomechanical effect. According to this effect, a bending of a bimaterial microcantilever takes place when temperature of an absorbing plate is changed. The bending occurs due to a difference between the coefficients of thermal expansion of a pair of materials from which the bimaterial microcantilever is fabricated (in the M3-50 FPA such materials are nonstoichiometric silicon nitride and aluminium).

Submicron thickness microminiature membrane of silicon nitride covered with a thin nichrome film is used as the absorbing plate. The same plate is used as a mirror while reading out the FPA in visible spectral range. Temperature change of a source of IR-radiation by 1 K causes membrane deflection by several hundreds of nanometers in the similar IR-detectors [1–4] that can be quite reliably registered by modern instruments.

The image of a single bimaterial sensing element of the infrared FPA (see Fig. 1b) is obtained with the optical profiler (white-light interference microscope) Wyko NT9300 (Bruker, Germany) at high magnification [5, 6]. The membrane of increased rigidity is well seen in the figure. The membrane is suspended over a substrate with the microcantilevers. The distance between the membrane and the substrate makes approximately 0.5 μm. The through-holes in the membrane are intended for easier access of etchant to the sacrificial layer of SiO_2 during FPA fabrication. The highly reflective bimaterial regions with aluminium coating are clearly seen on the microcantilevers.

The output optical image created by the FPA is shown in Fig. 2. The image was registered (read out) with the optical profiler. The measurements were conducted in vacuum 10^{-3} Torr. FPA illumination was carried out by means of the blackbody simulator M316 (Mikron, USA) having temperature 50°C.

The used profiler provides a noncontact method of measurement of a surface topography with height dif-

[1] The article was translated by the authors.

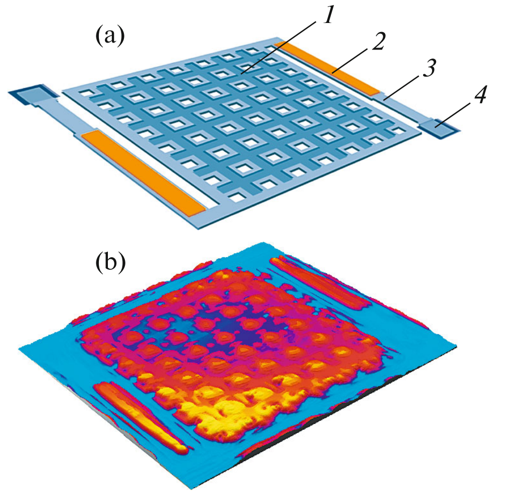

Fig. 1. Uncooled bimaterial sensing element of the infrared FPA M3-50. Sizes of the element are 50 × 50 μm^2. (a) Design of the sensing element: *1* is an absorbing membrane-reflector, *2* is a bimaterial region of the microcantilever, *3* is a thermoinsulation region of the microcantilever, *4* is an attaching point of the microcantilever to a substrate (anchor). (b) Image of the sensing element obtained with the optical profiler Wyko NT9300. Magnification ×101, HDVSI mode, stitching.

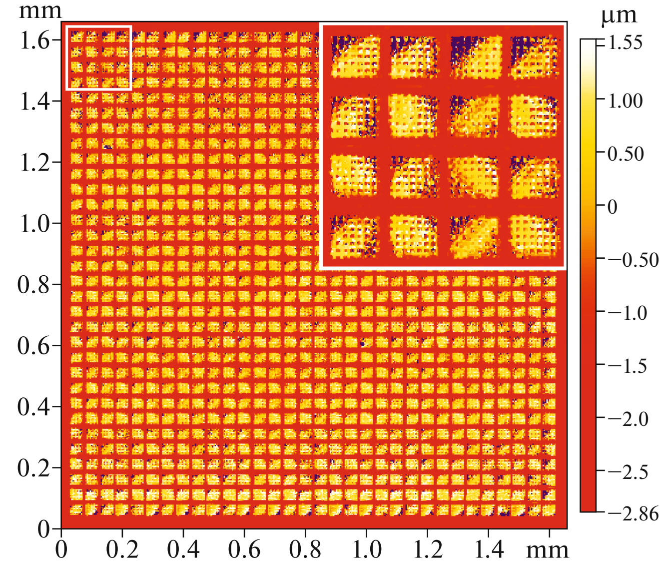

Fig. 2. Optical image 1738 × 1717 points of FPA M3-50 consisting of 32 × 32 uncooled bimaterial IR-detectors. The image is obtained with the optical profiler. Magnification ×10.2, HDVSI mode, stitching. Locations, where the profiler is unable to execute reading because of a large slope of membrane edges, are conditionally shown in black colour. The measurements were conducted in vacuum 10^{-3} Torr, the temperature of the blackbody simulator made 50°C.

ferences up to 10 mm. The utmost vertical resolution of the profiler makes 0.1 nm, lateral resolution—0.6 μm. Depending on the set magnification, fields of view of the instrument lay within the range from 4.6×3.5 mm^2 to 30×30 μm^2. The magnification is changed stepwise from ×1.4 to ×230 by sets of interchangeable interferometric objectives and interchangeable eyepieces. When using a vacuum chamber, the maximum magnification is limited to ×20.

The measurements of optical responses from the bimaterial MOMS IR-detectors are carried out in the mode of vertical scanning interferometry (VSI) or in the mode of high definition vertical scanning interferometry (HDVSI) [5, 7]. The latter mode combines subnanometer vertical resolution with a large vertical measurement range of topography height (tens of microns). The picture shown in Fig. 2 is FPA reaction on a uniform illumination from a radiating area of the blackbody simulator. Projection of the radiating area of the blackbody simulator on the FPA is implemented by means of the germanium objective Macro-70.

FPA testing in the vacuum chamber of the scanning electron microscope (SEM) JSM-6490LV (Jeol, Japan), during which direct heating/cooling of the FPA through the substrate was carried out with the heating stage MK3 (Deben, England), has shown that the sensitivity of the operating bimaterial IR-detectors corresponds to the sensitivity of the similar detectors known in the literature (tens-hundreds of nanometers per Kelvin) [1, 2]. SEM-revealed failure cause of some part of the IR-detectors was incomplete removal of the sacrificial layer of SiO_2.

2. PROBLEM FORMULATION

Since the sensing elements that directly form the image occupy approximately 70% of the area of the entire FPA, the obtained optical image would include a large number of points, which do not carry any useful information about the imaged IR-object (see Figs. 1, 2). Spaces between the IR-detectors and the regions occupied by the elements of the membrane suspension (sections of thermoinsulation of the microcantilevers, attachment points of the microcantilevers to the substrate) are such points. Thus, before an operator would receive a final picture, the digitized optical image of the FPA should be subjected to a mathematical treatment during which all the information not related to the observed IR-scene should be eliminated from the image.

Since the surface image of each membrane consists of many points (from hundreds to several thousands) even at a low lateral magnification of the profiler, this set of points should be presented by a single point on the output image. Thus, the image having dimensionality of the original FPA, i. e., 32 × 32 points should be obtained at the output of the program of mathematical treatment, where brightness of each point on such image is a mean value of brightnesses of the points belonging to the corresponding membrane.

It is worth noting that the optical profiler used for the measurements is unable to build an image of the surface sloped greatly to the horizontal plane as light after reflection from the sloped regions of such surface would to be unable to come back into the profiler's objective [6, 7]. Depending on objective magnification, the critical angle of the surface slope would make from 2° (Michelson objective ×2.5) to 35° (Mirau objective ×100). Since the membranes-reflectors of the fabricated FPA are not ideally flat and often have curved edges caused by residual internal stresses, the points corresponding to the strongly curved membrane edges are not imaged with the profiler. Such points are conditionally shown on the output image in black colour (see inset in Fig. 2). Thus, the mentioned black points should be ignored while determining a mean brightness across the surface of a membrane-reflector.

Analysis of the above formulated problem peculiarities shows that methods of recognition should be used for effective computer processing of the obtained image. To build an adequate recognition algorithm, it was first decided to conduct a mathematical treatment of the image by means of an already existing recognition program and then, based on the got experience, to formulate requirements to the algorithm and to write own recognition program which could be later built into a commercial device.

3. MATHEMATICAL PROCESSING OF THE OPTICAL IMAGE

The program of feature-oriented scanning (FOS) [8, 9] developed at the Institute of Physical Problems named after F.V. Lukin was used as the recognition program. The main purpose of the FOS program is control of a scanning probe microscope (SPM) and conduction of ultra-precise measurements of topography and surface properties at the nanoscale. At present, the FOS program is used at the Solid Nanotechnology Laboratory of the above mentioned institute and controls the commercial instrument Solver™ P4 (NT-MDT, Russia).

Besides real scanning mode, the FOS program has a mode of virtual scanning. In this mode, an image of a surface topography (real or synthesized) is fed into the program input, after that the program "scans" and recognizes the image by simulating operation of the probe microscope. In our case, the optical image obtained on the profiler (see Fig. 2) was fed at the input of the FOS program. In such image, the separate IR-detectors (membranes-reflectors) of the FPA under recognition are considered as surface features. The surface features are used by the FOS program as reference points.

The FOS program was slightly adapted to the considered problem. In particular, due to a large number of points in the membrane's optical image obtained in the stitching mode, the operational sizes of segments and apertures were increased (segment is a small square scan comprising one surface feature only; aperture is a square scan comprising several neighboring features [8, 9]). Aperture sizes made 64 × 64 points and more. The sizes used in the SPM are usually less than the pointed out especially when operating at the resolution limit of the microscope. The limit number of saddle points analysed during the recognition in the aperture was also increased. This increasing could be explained by probable increasing of aperture sizes while searching for the next feature. Typically, the difficulties while searching for the next feature occur in the virtual mode when a border of the image under recognition is "met."

Since the FPA image created by the profiler has very noisy areas, the FOS program performs smoothing before the recognition. The smoothing allows increasing a probability of the correct recognition and accuracy of determination of the membrane coordinates. A duplicate of the analysed surface area is subjected to the smoothing, the following calculation of the mean brightness is only carried out by the original image.

Roughness of the FPA surface is essentially higher at the edges of the elements of the IR-detectors. The roughness at these locations is caused by imperfections and inhomogeneities appeared during microlithographic operations. High roughness on strongly sloped regions enables at least a small part of the incident light to be reflected back into the profiler objective by making the strongly sloped regions to be partially visible [6]. The surface points invisible by the profiler are conditionally shown in black colour which symbolizes a practically complete absence of a useful signal (noise of the profiler's registration system). High roughness on horizontal regions only worsens the image since much of the light is scattered in different directions and just a part of the beam light incident upon the surface comes back into the profiler objective. Frequently, single bright topography points, which heights essentially exceed heights of neighboring points, can be observed on the regions with high roughness, especially in the HDVSI mode. As a rule, these points do not correspond to points of a physical surface and are artifacts introduced by the instrument.

The result of the FOS program operation (see Fig. 3) is an FPA image assembled of separate fragments (segments). For correct recognition, the black points were temporarily replaced with the white ones. Since the fragments are partially overlapped and the relative coordinates between them are precisely determined by the FOS program, the reconstructed image has no distinctions from the original one. The image shown in Fig. 2 is the original image. The number of points in the original image was decreased from 1738 × 1717 to 435 × 433 by means of interpolation in order to increase FOS productivity. At the current stage of the

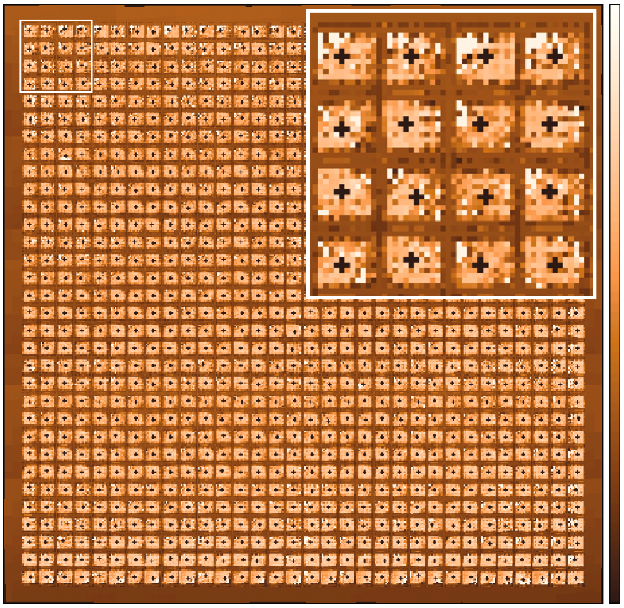

Fig. 3. Result of recognition of the infrared FPA by the FOS program. The surface image is assembled of separate fragments (segments). Recognized elements of the FPA (membranes) are marked with a "+" sign. At the time of recognition, the black points were replaced with the white ones.

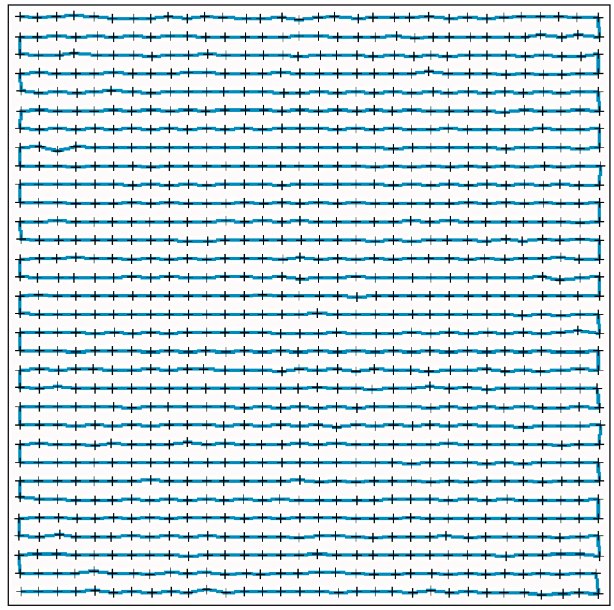

Fig. 4. Raster-like trajectory of connection of the features in a chain. The trajectory is created during virtual FOS. Positions of the detected features (FPA membranes) are marked with a "+" sign.

development, some loss of accuracy due to decrease in number of points of the analysed image is not critical.

In Fig. 3, the recognized elements of the FPA (membranes) are marked with a "+" sign. As it seen from the figure, all the FPA elements were recognized. Along with the output data, the FOS program generates a report file, where detailed accompanying information on modes and parameters of the conducted virtual scanning is given. Moreover, recommendations generated by the FOS program to operator are also inserted in the report file. The recommendations regard to a possible alteration of the modes and parameters in order to do optimal the next program executions.

FOS allows automatically collecting statistical information characterizing the measured surface. After the virtual scanning of the infrared FPA, the report file reflects information about mean distance between membranes, mean sizes of the membranes and coverage degree of FPA surface by the membranes. Since the information on each membrane is stored in the form of a segment, more detailed postprocessing of these segments is possible, which allows to determine geometrical parameters and a value of response characterizing each membrane separately. The obtained information can be used for improvements in technology (control of sizes) as well as for quality control of the fabricated infrared FPAs (estimation of thermomechanical response).

The trajectory of connection of the features in a chain, which is automatically built during the FOS process, is shown in Fig. 4. Usually, the formed connection trajectory looks visually like a raster. When some membranes are absent at their predefined positions, for example, as in case of imperfect infrared FPAs, the regular path of the connection trajectory will be disturbed. It does not matter for the FOS method, how the topography elements under recognition are arranged. Thus, an order violation in arrangement of the sensing elements in the imperfect FPA would not effect on the final result of the computer processing. This means that any *a priori* information on mutual arrangement of the sensing elements of the analyzed FPA is not required.

In the chain acquired during FOS, coordinates of each next membrane relative to position of the previous one are known. Moreover, each membrane has a segment—a small-sized image of the membrane. Possessing this information, one can reconstruct the original FPA image (see Fig. 3). The trajectory of "SPM-probe movement" from one feature to another during the virtual scanning (recognition) of the optical image of the infrared FPA is shown in Fig. 5. The trajectory includes only the "probe" movements between the surface features (membranes); movements in the local scans (apertures and segments) are not shown.

The sought for optical image of 32 × 32 points formed by the infrared FPA is shown in Fig. 6. Each image point (points have a square shape) represents a response of the corresponding bimaterial IR-detector shown in Fig. 2. The dark points represent detectors

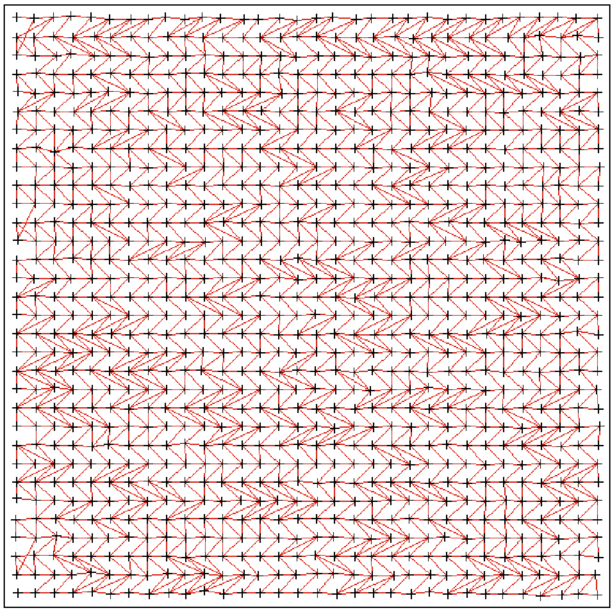

Fig. 5. Trajectory of "SPM-probe movement" during the virtual FOS (recognition) of the optical image of the infrared FPA. Positions of the detected features (FPA membranes) are marked with a "+" sign.

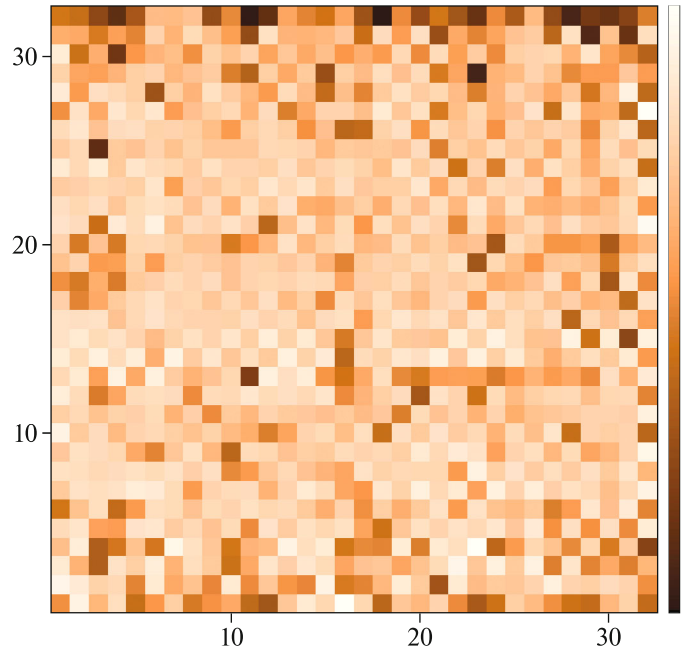

Fig. 6. Required image of 32 × 32 points given by the infrared 32 × 32 FPA uniformly illuminated by the IR-source (blackbody simulator) at temperature 50°C. Each point represents a response from the corresponding bimaterial IR-detector (points are depicted as squares). The image was obtained as a result of computer processing conducted according to the FOS method. The dark points correspond to strongly deformed membranes of the bimaterial IR-detectors.

with heavily deformed membranes. Usually, the membrane deformation looks like edge curving, it is caused by a hogging. The hogging is induced by uncompensated mechanical stresses in the membrane appeared during device fabrication.

The sought for image is built by a surface assembler adapted to the task under consideration. The surface assembler is a special program being part of the FOS software package which builds a reconstructed surface image of segments. In particular, the image shown in Fig. 3 was built by the surface assembler. Adaptation of the surface assembler used for building of the output image shown in Fig. 6 consisted in the following. Instead of image assembling of segments, the image was assembled of points which brightnesses were set equal to mean brightnesses of the points of the recognized membrane-reflectors (brightnesses of the black points were ignored).

Taking into account the obtained results, one can conclude that the FOS program initially developed for accurate measurement of a surface topography with an SPM is quite suitable for solving the problem put by. Nevertheless, several system peculiarities of this program operation should be noted which can sometimes manifest itself not the best way during program run with the infrared FPA. First of all, one should take into account that FOS uses surface features as reference points while moving across a surface only to measure surface topography in some sample area preset by operator. The surface topography is measured by parts, i. e., with small segments in the center of which surface features (membranes of the IR-detectors in our case) detected during the scanning are located.

Such approach allows to exclude a number of errors from SPM-measurements, in particular, errors that are caused by thermal drifts of elements of microscope design; errors that relate to creeps of piezoscanner manipulators; errors that are generated by manipulator nonlinearities and spurious cross couplings between the manipulators. Moreover, the FOS approach allows significantly reducing noise influence on the measurement results and significantly improving instrument resolution. It is clear that the most of the problems solving by FOS in SPM can not be applied to the mathematical treatment of the infrared FPAs. Therefore, the FOS has a certain functional redundancy.

Since the primary FOS aim is acquisition of a continuous undistorted image of a surface topography, which assemblage is carried out of separate fragments, it does not matter for FOS to which particular features these separate segments belong to. It is only important for FOS that there will be no gaps between the neighboring segments after their superimposition. Therefore, during program execution, it can ignore some features occurring on its way if the resulting image can be assembled without gaps. Since in our task the surface features, which the FOS program uses as reference points, are membranes-reflectors of the sensing elements, some of the membranes can be missed by the program in certain cases.

As a rule, feature missing takes place at the sites with significant FPA defects. In that case, an additional program adjustment is required. The significant defects are: a complete absence of one or several sensing elements; a strong mechanical damage (destruction) of a sensing element or its very strong hogging.

4. CONCLUSIONS

The distinctive property of the FOS program is that for normal operation of the program, no a priori information on arrangement of features (membranes of the sensing elements) is required. Moreover, the FOS program allows automatically collecting statistics characterizing IR-detectors of the FPA that is important for analysis of experimental results, FPA fabrication technology adjustment, and for FPA outgoing inspection.

With a uniform illumination of the FPA by IR-radiation, for example, from an extended radiating plate of a blackbody simulator, the obtained array of signals of the output image can be used for correction of unequal thermomechanical sensitivity of the FPA detectors. The information on sensitivity of each detector can be stored in an IR-camera memory and then it can be taken into account for each frame processing. The response inequality among the bimaterial IR-detectors is caused by the always taking place technological variation of sizes, differences in composition and structure of the used materials, inhomogeneity of the treatment methods over wafer surface, etc.

Since the exact membrane location in the FPA is a priori known (defined at the designing stage), the above mentioned algorithm universality is not so important for image processing of the FPAs that have passed a final inspection. Taking into consideration that the price for the universality of the program is its performance, a specialized program for processing the optical image will be created at the next development stage. This program will be far less versatile than the currently applied FOS program but it will be much more productive that will allow it to be embedded into microcontroller of a commercial device.

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