

METHOD TO REDUCE ADHESION BETWEEN A CONFORMABLE REGION AND A PATTERN OF A MOLD

BACKGROUND OF THE INVENTION

[0001] The field of invention relates generally to micro-fabrication of structures. More particularly, the present invention is directed to patterning substrates in furtherance of the formation of structures.

[0002] Micro-fabrication involves the fabrication of very small structures, e.g., having features on the order of micro-meters or smaller. One area in which micro-fabrication has had a sizeable impact is in the processing of integrated circuits. As the semiconductor processing industry continues to strive for larger production yields while increasing the circuits per unit area formed on a substrate, micro-fabrication becomes increasingly important. Micro-fabrication provides greater process control while allowing a reduction in the minimum feature dimension of the structures formed. Other areas of development in which micro-fabrication has been employed include biotechnology, optical technology, mechanical systems and the like.

[0003] An exemplary micro-fabrication technique is shown in United States patent number 6,334,960 to Willson et al. Willson et al. disclose a method of forming a relief image in a structure. The method includes providing a substrate having a transfer layer. The transfer layer is covered with a polymerizable fluid composition. A mold makes mechanical contact with the polymerizable fluid. The mold includes a relief structure, and the polymerizable fluid composition fills the relief structure. The polymerizable fluid composition is then subjected to conditions to solidify



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and polymerize the same, forming a solidified polymeric material on the transfer layer that contains a relief structure complimentary to that of the mold. The mold is then separated from the solid polymeric material such that a replica of the relief structure in the mold is formed in the solidified polymeric material. The transfer layer and the solidified polymeric material are subjected to an environment to selectively etch the transfer layer relative to the solidified polymeric material such that a relief image is formed in the transfer layer.

[0004] An important characteristic with accurately forming the pattern in the polymeric material is to reduce, if not prevent, adhesion of the polymeric material, and/or, transfer layer, to the mold. These are referred to as release characteristics. In this manner, the pattern recorded in the polymeric material and/or transfer layer is not distorted during separation of the mold therefrom. To improve the release characteristics, Willson et al. form a release layer on the surface of the mold. The release layer is typically hydrophobic and/or has low surface energy. The release layer adheres to the mold and to either the transfer layer or the polymeric material. Providing the transfer layer with improved release characteristics minimizes distortions in the pattern recorded into the polymeric material and/or the transfer layer that are attributable to mold separation. This type of release layer is referred to, for purposes of the present discussion, as an *a priori* release layer, i.e., a release layer that is solidified to the mold.

[0005] Another prior art attempt to improve release characteristics is described by Bender et al. in Multiple Imprinting in UV-based Nanoimprint Lithography: Related

Material Issues, Microelectronic Engineering 61-62 (2002), pp. 407-413. Specifically, Bender et al. employ a mold having an *a priori* release layer in conjunction with a fluorine-treated UV curable material. To that end, a UV curable layer is applied to a substrate by spin-coating a 200 CPS UV curable fluid to form a UV curable layer. The UV curable layer is enriched with fluorine groups to improve the release characteristics.

[0006] *A priori* release layers, however, typically have a limited operational life. As a result, a single mold may be coated multiple times with an *a priori* release layer. This can result in several hours of down-time for a given mold, reducing throughput. Additionally, the molecular structure of the *a priori* release layer may limit the minimization of the minimum feature dimension that is printed.

[0007] There is a need, therefore, to improve the release characteristics of a mold employed in imprint lithography processes.

SUMMARY OF THE INVENTION

[0008] The present invention provides a method to reduce adhesion between a substrate and a pattern of a mold. The method features forming a conformable material on the substrate and contacting the conformable material with the surface. A conditioned layer is formed from the conformable material. The conditioned layer has first and second sub-portions, with the first sub-portion being solidified and the second sub-portion having a first affinity for the surface and a second affinity for the first sub-portion. The first is greater than the second affinity. In this fashion, upon separation of the mold from the conditioned layer, a subset of the second sub-portion maintains contact with the mold, thereby reducing

the probability that a pattern formed in the conditioned layer becomes compromised. These and other embodiments are described herein.

BRIEF DESCRIPTION OF THE DRAWINGS

[0009] Fig. 1 is a perspective view of a lithographic system in accordance with the present invention;

[0010] Fig. 2 is a simplified elevation view of a lithographic system shown in Fig. 1;

[0011] Fig. 3 is a simplified representation of material from which an imprinting layer, shown in Fig. 2, is comprised before being polymerized and cross-linked;

[0012] Fig. 4 is a simplified representation of cross-linked polymer material into which the material shown in Fig. 3 is transformed after being subjected to radiation;

[0013] Fig. 5 is a simplified elevation view of a mold spaced-apart from the imprinting layer, shown in Fig. 1, after patterning of the imprinting layer;

[0014] Fig. 6 is a simplified elevation view of imprint material disposed on a substrate in accordance with the present invention;

[0015] Fig. 7 is a simplified elevation view of imprint material disposed on a substrate in accordance with an alternate embodiment;

[0016] Fig. 8 is a simplified elevation view of imprint material, shown in Fig. 6, after contact with the mold; and

[0017] Fig. 9 is a flow diagram showing pattern priming in accordance with an alternate embodiment of the present invention.

DETAILED DESCRIPTION OF THE INVENTION

[0018] Fig. 1 depicts a lithographic system 10 in accordance with one embodiment of the present invention

that includes a pair of spaced-apart bridge supports 12 having a bridge 14 and a stage support 16 extending therebetween. Bridge 14 and stage support 16 are spaced-apart. Coupled to bridge 14 is an imprint head 18, which extends from bridge 14 toward stage support 16. Disposed upon stage support 16 to face imprint head 18 is a motion stage 20. Motion stage 20 is configured to move with respect to stage support 16 along X and Y axes. A radiation source 22 is coupled to system 10 to impinge actinic radiation upon motion stage 20. As shown, radiation source 22 is coupled to bridge 14 and includes a power generator 23 connected to radiation source 22.

[0019] Referring to both Figs. 1 and 2, connected to imprint head 18 is a template 26 having a mold 28 thereon. Mold 28 includes a plurality of features defined by a plurality of spaced-apart recessions 28a and protrusions 28b. The plurality of features defines an original pattern that is to be transferred into a substrate 31 positioned on motion stage 20. Substrate 31 may comprise of a bare wafer or a wafer with one or more layers disposed thereon. To that end, imprint head 18 is adapted to move along the Z axis and vary a distance "d" between mold 28 and substrate 31. In this manner, the features on mold 28 may be imprinted into a conformable region of substrate 31, discussed more fully below. Radiation source 22 is located so that mold 28 is positioned between radiation source 22 and substrate 31. As a result, mold 28 is fabricated from material that allows it to be substantially transparent to the radiation produced by radiation source 22.

[0020] Referring to both Figs. 2 and 3, a conformable region, such as an imprinting layer 34, is disposed on a portion of surface 32 that presents a substantially

planar profile. It should be understood that the conformable region may be formed using any known technique to produce conformable material on such as a hot embossing process disclosed in United States patent number 5,772,905 to Chou, which is incorporated by reference in its entirety herein, or a laser assisted direct imprinting (LADI) process of the type described by Chou et al. in Ultrafast and Direct Imprint of Nanostructures in Silicon, Nature, Vol. 417, pp. 835-837, June 2002. In the present embodiment, however, conformable region consists of imprinting layer 34 being deposited as a plurality of spaced-apart discrete droplets 36 of material 36a on substrate 31, discussed more fully below. Imprinting layer 34 is formed from a material 36a that may be selectively polymerized and cross-linked to record the original pattern therein, defining a recorded pattern. Material 36a is shown in Fig. 4 as being cross-linked at points 36b, forming cross-linked polymer material 36c.

[0021] Referring to Figs. 2, 3 and 5, the pattern recorded in imprinting layer 34 is produced, in part, by mechanical contact with mold 28. To that end, imprint head 18 reduces the distance "d" to allow imprinting layer 34 to come into mechanical contact with mold 28, spreading droplets 36 so as to form imprinting layer 34 with a contiguous formation of material 36a over surface 32. In one embodiment, distance "d" is reduced to allow sub-portions 34a of imprinting layer 34 to ingress into and fill recessions 28a.

[0022] To facilitate filling of recessions 28a, material 36a is provided with the requisite properties to completely fill recessions 28a while covering surface 32 with a contiguous formation of material 36a. In the

present embodiment, sub-portions 34b of imprinting layer 34 in superimposition with protrusions 28b remain after the desired, usually minimum distance "d", has been reached, leaving sub-portions 34a with a thickness t_1 , and sub-portions 34b with a thickness, t_2 . Thicknesses " t_1 " and " t_2 " may be any thickness desired, dependent upon the application. Typically, t_1 is selected so as to be no greater than twice the width u of sub-portions 34a, i.e., $t_1 \leq 2u$, shown more clearly in Fig. 5.

[0023] Referring to Figs. 2, 3 and 4, after a desired distance "d" has been reached, radiation source 22 produces actinic radiation that polymerizes and cross-links material 36a, forming polymer material 36c in which a substantial portion thereof is cross-linked. As a result, material 36a transforms to material 36c, which is a solid, forming imprinting layer 134, shown in Fig. 5. Specifically, material 36c is solidified to provide side 34c of imprinting layer 134 with a shape conforming to a shape of a surface 28c of mold 28, with imprinting layer 134 having recesses 30. After imprinting layer 134 is transformed to consist of material 36c, shown in Fig. 4, imprint head 18, shown in Fig. 2, is moved to increase distance "d" so that mold 28 and imprinting layer 134 are spaced-apart.

[0024] Referring to Fig. 5, additional processing may be employed to complete the patterning of substrate 31. For example, substrate 31 and imprinting layer 134 may be etched to transfer the pattern of imprinting layer 134 into substrate 31, providing a patterned surface (not shown). To facilitate etching, the material from which imprinting layer 134 is formed may be varied to define a relative etch rate with respect to substrate 31, as desired.

[0025] To that end, imprinting layer 134 may be provided with an etch differential with respect to photo-resist material (not shown) selectively disposed thereon. The photo-resist material (not shown) may be provided to further pattern imprinting layer 134, using known techniques. Any etch process may be employed, dependent upon the etch rate desired and the underlying constituents that form substrate 31 and imprinting layer 134. Exemplary etch processes may include plasma etching, reactive ion etching, chemical wet etching and the like.

[0026] Referring to both Figs. 1 and 2, an exemplary radiation source 22 may produce ultraviolet radiation; however, any known radiation source may be employed. The selection of radiation employed to initiate the polymerization of the material in imprinting layer 34 is known to one skilled in the art and typically depends on the specific application which is desired. Furthermore, the plurality of features on mold 28 are shown as recessions 28a extending along a direction parallel to protrusions 28b that provide a cross-section of mold 28 with a shape of a battlement. However, recessions 28a and protrusions 28b may correspond to virtually any feature required to create an integrated circuit and may be as small as a few tenths of nanometers.

[0027] Referring to Figs. 1, 2 and 5, the pattern produced by the present patterning technique may be transferred into substrate 31 to provide features having aspect ratios as great as 30:1. To that end, one embodiment of mold 28 has recessions 28a defining an aspect ratio in a range of 1:1 to 10:1. Specifically, protrusions 28b have a width W_1 in a range of about 10 nm to about 5000 μm , and recessions 28a have a width W_2 in a

range of 10 nm to about 5000 μm . As a result, mold 28 and/or template 26, may be formed from various conventional materials, such as, but not limited to, fused-silica, quartz, silicon, organic polymers, siloxane polymers, borosilicate glass, fluorocarbon polymers, metal, hardened sapphire and the like.

[0028] Referring to Figs. 1, 2 and 3, the characteristics of material 36a are important to efficiently pattern substrate 31 in light of the unique deposition process employed. As mentioned above, material 36a is deposited on substrate 31 as a plurality of discrete and spaced-apart droplets 36. The combined volume of droplets 36 is such that the material 36a is distributed appropriately over an area of surface 32 where imprinting layer 34 is to be formed. As a result, imprinting layer 34 is spread and patterned concurrently, with the pattern being subsequently set into imprinting layer 34 by exposure to radiation, such as ultraviolet radiation. As a result of the deposition process, it is desired that material 36a have certain characteristics to facilitate rapid and even spreading of material 36a in droplets 36 over surface 32 so that all thicknesses t_1 are substantially uniform and all thicknesses t_2 are substantially uniform. The desirable characteristics include having a low viscosity, e.g., in a range of 0.5 to 5 centipoise (csp), as well as the ability to wet surface of substrate 31 and/or mold 28 and to avoid subsequent pit or hole formation after polymerization. With these characteristics satisfied, imprinting layer 34 may be made sufficiently thin while avoiding formation of pits or holes in the thinner regions, such as sub-portions 34b, shown in Fig. 5.

[0029] The constituent components that form material 36a to provide the aforementioned characteristics may differ. This results from substrate 31 being formed from a number of different materials. As a result, the chemical composition of surface 32 varies dependent upon the material from which substrate 31 is formed. For example, substrate 31 may be formed from silicon, plastics, gallium arsenide, mercury telluride, and composites thereof. Additionally, substrate 31 may include one or more layers in sub-portion 34b, e.g., dielectric layer, metal layer, semiconductor layer, planarization layer and the like.

[0030] Referring to Figs. 1, 2 and 3, an exemplary composition for material 36a is as follows:

COMPOSITION 1

isobornyl acrylate

n-hexyl acrylate

ethylene glycol diacrylate

2-hydroxy-2-methyl-1-phenyl-propan-1-one

In an exemplary composition, isobornyl acrylate comprises approximately 55% of the composition, n-hexyl acrylate comprised approximately 27%, ethylene glycol diacrylate comprises approximately 15% and the initiator 2-hydroxy-2-methyl-1-phenyl-propan-1-one comprised approximately 3%. The initiator is sold under the trade name DAROCUR® 1173 by CIBA® of Tarrytown, New York. The above-identified composition also includes stabilizers that are well known in the chemical art to increase the operational life of the composition. To provide suitable release properties, COMPOSITION 1 is typically employed with a template treated to have a mold surface that is

hydrophobic and/or low surface energy, i.e. an *a priori* release layer.

[0031] To improve the release properties of mold 28 and imprinting layer 34 and to ensure that imprinting layer 34 does not adhere to mold 28, the composition from which material 36a is formed may include an additive that reduces the surface tension of COMPOSITION 1. To that end, material 36a may include, as an additive, a surfactant. For purposes of this invention a surfactant is defined as any molecule, one tail of which is hydrophobic. Surfactants may be either fluorine containing, e.g., include a fluorine chain, or may not include any fluorine in the surfactant molecule structure. An exemplary surfactant is available under the trade name ZONYL® FSO-100 from DUPONT™ that has a general structure of R_1R_2 where $R_1 = F(CF_2CF_2)_y$, with y being in a range of 1 to 7, inclusive and $R_2 = CH_2CH_2O(CH_2CH_2O)_xH$, where x is in a range of 0 to 15, inclusive. This provides material 36a with the following composition:

COMPOSITION 2

isobornyl acrylate

n-hexyl acrylate

ethylene glycol diacrylate

2-hydroxy-2-methyl-1-phenyl-propan-1-one

$R_fCH_2CH_2O(CH_2CH_2O)_xH$,

The ZONYL® FSO-100 additive comprises less than 1% of the composition, with the relative amounts of the remaining components being as discussed above with respect to

COMPOSITION 1. However, the percentage of ZONYL® FSO-100 may be greater than 1%.

[0032] An advantage provided by COMPOSITION 2 is that it abrogates the need for an *a priori* release layer, i.e., a separate hydrophobic and/or low surface energy release layer disposed on mold 28. Specifically, COMPOSITION 2 provides desirable release properties to mold 28 and imprinting layer 34 so that material 36c, shown in Fig. 4, does not adhere to mold 28 with sufficient force to distort the pattern recorded therein. It is believed that the ZONYL® FSO-100 becomes concentrated in a first region of material 36a, shown in Fig. 3. The polymerizable compound becomes concentrated in a second region of material 36a.

[0033] Referring to Fig. 6 droplets 36 would have a higher concentration of the ZONYL® FSO-100 additive in region 136, compared with region 137, in which the polymerizable compound is concentrated. Were spin-on techniques employed, the additive would be concentrated in a region 236, and the polymerizable compound being concentrated in region 237, shown in Fig. 7.

[0034] Referring to Figs. 3, 4 and 8, regardless of the deposition process involved, upon contact with material 36a and exposure to actinic radiation, material 36a is transformed to material 36c and a first interface 136a is defined between region 136 and mold 28. A second interface 137a is formed between regions 136 and 137. It is believed that some portion of material 36c associated with region 136, if not all, has an affinity for the mold 28 that is greater than the attraction between that portion and the material 36c associated with region 137. As a result, upon separation of mold 28 from material 36c, a sub-section, or all of sub-portions 34a and 34b,

shown in Fig. 5, separates from region 137, thereby minimizing damage to the pattern recorded in material 36c due to adhesion forces between mold 28 and material 36c.

[0035] Specifically, interface 136a defines a first interfacial energy step associated therewith, and second interface 137a defines a second interfacial energy step, with the first interfacial energy step being greater than the second interfacial energy step. The first interfacial energy step is defined by the difference in surface energy of mold 28 and surface tension of material 36c in region 136. The second interfacial surface energy is defined by the adhesion of material 36c associated with region 136 for material 36c associated with region 137. In the present example, COMPOSITION 2 provides region 136 with a surface tension in a range of 20-35 milli-Newtons/meter, with one milli-Joule/cm² = 1 milli-Newton/meter. As a result, the interfacial surface energy step at interface 136a is sufficiently large to overcome the interfacial energy step at interface 137.

[0036] Referring to Fig. 2, an additional advantage provided by COMPOSITION 2 is that the time required to wet mold 28 and, therefore, spread droplets 36 may be reduced. Specifically, by abrogating the need to have an *a priori* release layer on mold 28, the surface of mold 28 may be provided with a high surface energy, e.g., 60 to 250 milli-Newtons/meter. The wettability of the surface of mold 28 for COMPOSITION 2, as defined by the contact angle method, may be in a range of 10 degrees or less. This minimizes the time required to fill the features of the pattern on mold 28. Further, the ZONYL[®] FSO-100 additive provides COMPOSITION 2 with a wettability, as defined by the contact angle method, in a range of 75 to 90 degrees, thereby augmenting the wettability of mold

28, thereby further reducing the time required to spread droplets 36. Of course, COMPOSITION 2 may be employed with an *a priori* release layer, such as those known in the prior art, to further improve release properties.

[0037] Another manner by which to improve the release properties of mold 28 includes conditioning the pattern of mold 28 by exposing the same to a conditioning mixture including an additive that will remain on mold 28 to reduce the surface energy of the mold surface. An exemplary additive is a surfactant.

[0038] In a specific example, mold 28 was exposed to a mixture that included approximately 0.1% or more of ZONYL® FSO-100 with the remainder comprising isopropyl alcohol (IPA). Exposure of the pattern may be achieved by virtually any manner known in the art, including dipping the pattern into a volume of the conditioning mixture, wiping the pattern with a cloth saturated with the conditioning mixture and spraying a stream of the conditioning mixture onto the surface. The IPA in the conditioning mixture is then allowed to evaporate before using the mold 28. In this manner, the IPA facilitates removing, from the pattern, undesired contaminants while leaving the additive, thereby conditioning the surface of the pattern. The conditioning mixture may be employed with COMPOSITION 2 to augment improvement of the release properties provided by COMPOSITION 2. The additive in the conditioning mixture may be the same or differ from the additive in COMPOSITION 2. Alternatively, the conditioning mixture may be employed with COMPOSITION 1, or any other polymerizable material suitable for imprint lithography, as well as other imprint processes such as the hot embossing and laser assisted imprint processes.

[0039] Another technique for conditioning the pattern of mold 28 employs pattern priming. Pattern priming is achieved by selectively contacting the conformable region with the pattern a sufficient number of times to accurately reproduce, in the conformable region, a pattern complementary to the initial pattern. Specifically, it was found that by repeatably contacting imprint material 36a, shown in Fig. 3, the complementary pattern formed improves with each successive imprint. After a sufficient number of imprints, an accurate complementary reproduction of the pattern in mold 28 is formed. The pattern priming technique may be employed in combination with the aforementioned conditioning mixture and either COMPOSITION 1 or COMPOSITION 2 and, or with COMPOSITION 2, alone, i.e., COMPOSITION 2 without use of the conditioning mixture. It is believed that the number of imprints required to be produced before an accurate complementary reproduction of the pattern occurs is inversely proportional to the quantity of additive in COMPOSITION 2. Specifically, it is believed that by increasing the quantity of the additive in COMPOSITION 2 that the number of imprints required before an accurate complementary reproduction of the pattern occurs.

[0040] Referring to Figs. 2 and 9, in operation, imprint priming would include forming a conformable material on a first substrate, defining a priming substrate at step 300. At step 302, mold 28 contacts the conformable region a sufficient number of times to accurately reproduce, in the conformable material on the priming substrate, the pattern on mold 28. In one example, mold 28 is placed in contact with a first sub-portion of the conformable material. Thereafter, the first sub-portion is polymerized and mold 28 is spaced-

part therefrom. Mold 28 is then placed in contact with a second sub-portion of the conformable material, which is spaced-apart from the first sub-portion. The conformable material associated with the second sub-portion is polymerized and the process is repeated until an accurate pattern is recorded in the conformable material that is complementary to the pattern on mold 28. In this manner a primed mold is generated. At step 304 the primed mold is placed in contact with conformable material on a second substrate, referred to as a process substrate. Thereafter, the pattern may be recorded therein by polymerizing the conformable material using well known imprint lithography techniques. In this manner, the primed mold may be employed to complete the patterning of the process substrate.

[0041] The embodiments of the present invention described above are exemplary. Many changes and modifications may be made to the disclosure recited above, while remaining within the scope of the invention. The scope of the invention should, therefore, be determined not with reference to the above description, but instead should be determined with reference to the appended claims along with their full scope of equivalents.

Claims:

1. A method of reducing adhesion forces between a conformable material on a substrate and a mold having an initial pattern, said method comprising:
forming said conformable material on said substrate by depositing, upon said substrate, a conformable composition having a polymerizable compound and non-ionic surfactant molecules, with said non-ionic surfactant molecules being concentrated in a first region of said conformable material with said polymerizable compound being concentrated in a second region of said conformable composition;
contacting said conformable material with said mold; and
solidifying said polymerizable compound, defining solidified material with said first region being positioned between said second region and said mold and a subset of said non-ionic surfactant molecules having an affinity for said mold that is greater than an affinity for said solidified material.
2. The method as recited in claim 1 further including conditioning said mold to be hydrophilic.
3. The method as recited in claim 1 further including conditioning said mold by exposing said mold to a mixture of isopropyl alcohol and said non-ionic surfactant.
4. The method as recited in claim 1 wherein forming said conformable material further includes depositing a plurality of drops of said conformable composition upon said substrate.
5. The method as recited in claim 1 wherein forming said conformable material further includes depositing said conformable composition upon said substrate employing spin-coating techniques.

6. The method as recited in claim 1 further including sequentially contacting said conformable composition a sufficient number of times to accurately reproduce, in said conformable composition, a recorded pattern complementary to said initial pattern.

7. The method as recited in claim 1 wherein forming said conformable material further includes forming said conformable composition from isobornyl acrylate, n-hexyl acrylate, ethylene glycol diacrylate and 2-hydroxy-2-methyl-1-phenyl-propan-1-one and R_1R_2 .

8. A method of reducing adhesion forces between a substrate and a mold having a patterned region with a surface, said method comprising:

forming a conformable material on said substrate;

contacting said conformable material with said surface; and

forming a conditioned layer from said conformable material having a first and second sub-portions, with said first sub-portion being solidified and said second sub-portion including a plurality of molecules, a subset of which forms hydrogen bonds with said surface generating a and defining a first affinity for said surface, with the molecules of said subset having a second affinity for said first sub-portion, such that said first affinity is greater than said second affinity.

9. The method as recited in claim 8 further including conditioning said mold to be hydrophilic before contacting said conformable material.

10. The method as recited in claim 8 further including conditioning said mold by exposing said mold to a mixture of isopropyl alcohol and a surfactant before contacting said conformable material.

11. The method as recited in claim 8 wherein forming said conformable material further includes depositing a plurality of drops of said conformable composition upon said substrate.

12. The method as recited in claim 8 wherein forming said conformable material further includes depositing said conformable composition upon said substrate employing spin-coating techniques.

13. The method as recited in claim 8 further including sequentially contacting said conformable composition a sufficient number of times to accurately reproduce, in said conformable composition, a recorded pattern complementary to said initial pattern.

14. The method as recited in claim 8 wherein forming said conformable material further includes forming said conformable composition from isobornyl acrylate, n-hexyl acrylate, ethylene glycol diacrylate and 2-hydroxy-2-methyl-1-phenyl-propan-1-one and R_1R_2 .