

FLOURINE REMOVAL BY ION EXCHANGE

CROSS-REFERENCE TO RELATED APPLICATIONS

This application claims the benefit of U.S. Provisional Application No. 60/168,962, filed December 3, 1999, and U.S. Provisional Application No. 60/177,827, filed January 25, 2000.

FIELD OF THE INVENTION

The present invention generally relates to the removal and collection of undesirable wastes produced as byproducts of industrial processes. More particularly, the present invention is directed to converting fluorine gas in chemical vapor used in semiconductor manufacturing processes to a disposable form thereof. In particular, the present invention is directed to a method and apparatus for use in removing and collecting fluorine that is produced in industrial processes. Additionally, the present invention includes a system using the method and apparatus of the present invention in industrial processes requiring the removal and collection of fluorine.

BACKGROUND OF THE INVENTION

Semiconductor manufacturing processes generally involve the use of Chemical Vapor Deposition during processing of dielectrics and metals. Certain parts of the manufacturing process also etch semiconductor components with chemical vapor, which typically consists of perfluorinated compounds (PFCs) and fluorine gas. The steps of the manufacturing process are typically achieved by specific tools, which are generally cleaned after a number of cycles. In many industrial processes, such as semiconductor manufacturing, some amounts of fluorine gas remain unutilized.

Fluorine gas is highly corrosive, and both elemental fluorine and the fluoride ion can be highly toxic. Accordingly, it is desirable to safely and efficiently remove and properly dispose of fluorine and/or fluoride used in industrial processes, and in semiconductor manufacturing processes in particular.

Current technologies for fluorine removal focus on scrubbing the fluorine gas with simple air scrubbers to produce a constant bleed of hydrofluoric acid (HF), which is generally sent to a manufacturing facility's Acid Waste Neutralization (AWN) system for processing and disposal. Because HF is a weak acid with a pK_a of 3.16, the transformation of F_2 to HF is discouraged at low pH values. This becomes problematic for scrubbers, as pH becomes the controlling mechanism for bleed volumes and consequently for concentration of HF. Further, increasing pH, such as by addition of alkali, poses further problems because OF_2 , an undesirable byproduct, can be produced in an alkaline environment in the presence of hypofluorous acid (HOF), which is also formed during the reaction of F_2 with water. Additionally, despite operating at maximum allowable concentrations of HF in the scrubber, the HF reaching the AWN is generally too dilute for optimal operation of fluorspar (CaF_2) precipitation systems. Further, large amounts of chemicals are consumed in conventional CaF_2 precipitation systems. Additionally, the sludge volume is very high due to the high level of hydration, requiring excessive CaF_2 sludge hauling.

Accordingly, there remains a need to provide a new and improved method and apparatus for removing and collecting fluorine and/or fluoride. There further remains a need for a system for removing fluorine which has a low operating cost and which generates a concentrated end product that can be hauled away economically. The present invention is directed to meeting these needs.

SUMMARY OF THE INVENTION

It is an object of the present invention to provide a new and useful method for removing fluorine gas from a selected environment.

It is another object to provide a low operating cost method for removing and disposing of undesirable byproducts of industrial processes.

It is yet another object of the present invention to provide a new and useful apparatus for removing and collecting fluorine and/or fluoride in selected manufacturing processes.

A still further object of the present invention is to provide an apparatus which generates a concentrated fluoride end-product that can be economically disposed of and that does not require excessive sludge hauling.

Yet another object of the present invention is to provide a system that removes fluorine gas from industrial manufacturing processes and provides a disposable end-product thereof.

In accordance with a first aspect of the invention, there is provided a method is provided for removing fluorine gas from a selected environment. The method comprises the steps of contacting the fluorine gas from the environment with a selected quantity of water, thereby to generate an acidic solution of hydrofluoric acid, and contacting the solution of hydrofluoric acid with an ion-exchange resin having an active state operative to exchange selected ions therein for fluoride ions in the solution when in contact therewith. A continuous stream of water may be contacted with a continuous stream of fluorine gas, such as by injecting the fluorine gas into the water. Where the selected environment includes silica particles, the method may include the step of filtering the solution of hydrofluoric acid through a porous strong base anion resin thereby to remove silica particles disposed in the solution.

The step of contacting the solution with the ion-exchange resin may be accomplished by passing the solution of hydrofluoric acid through a resin vessel in which the ion-exchange resin is disposed. The ion-exchange resin may be a weak-base anion exchange resin or a strong base anion exchange resin, and is preferably a crosslinked poly vinylpyridine resin or a derivative thereof, and more preferably a ReilleXTm 402 or ReilleXTm 425 resin. The method may include doping the ion-exchange resin with an electron donor catalyst, such as palladium or titanium. The step of doping may be accomplished by contacting the ion-exchange resin with a salt of the catalyst and thereafter contacting the ion-exchange resin with an oxidizing agent.

The ion-exchange resin may be capable of chemically shifting between the active state and an exhausted state operative to exchange the fluoride ions in the ion-exchange resin for the selected ions contained in a regenerant solution, such as an ammonium hydroxide solution, when in

contact therewith, wherein the method may include the step of regenerating the ion-exchange resin by contacting the ion-exchange resin with the regenerant solution thereby to form a selected regenerant waste product containing the fluoride ions, such as ammonium fluoride. The method may include the step of rinsing the ion-exchange resin with a rinse solution, such as de-ionized water, after the step of regenerating the ion-exchange resin. The rinse solution may thereafter be used to replenish the regenerant solution. The regenerant waste product may be collected in a storage vessel.

The solution of hydrofluoric acid may be cooled, such as by use of a heat-exchange apparatus, prior to the step of contacting the solution with the ion-exchange resin. A reducing agent may be added to the solution of hydrofluoric acid prior to the step of contacting the solution of hydrofluoric acid with the ion-exchange resin.

In accordance with a second aspect of the invention, there is provided an apparatus for use in removing fluorine from a selected environment. The apparatus comprises an inlet in communication with the selected environment and operative to provide fluorine gas therefrom, a conduit in communication with the inlet and adapted to receive fluorine gas therefrom and operative to transport an aqueous solution therethrough, a resin vessel in fluid communication with the conduit and operative to receive the aqueous solution therefrom, and an ionexchange resin disposed in the resin vessel and adapted to contact the aqueous solution. The ion-exchange resin has an active state operative to exchange selected ions therein for fluoride ions in the aqueous solution at the acidic pH when in contact therewith.

The inlet may include an injector, such as a vacuum pump or an eductor, that is operative to inject the fluorine gas into the conduit. The resin vessel may receive the aqueous solution in a fluid compartment thereof and further include a chamber proximate to the fluid compartment that is sized and adapted to permit a gas, such as N₂, disposed in the aqueous solution to separate therefrom and enter the chamber, which may be in communication with a scrubber operative to receive the gas from the chamber.

The ion-exchange resin for use in the apparatus is similar or identical to that for use in the method of the invention. When the ion-exchange resin is capable of chemically shifting between the active state and the exhausted state, the apparatus may include a regenerant source vessel adapted to receive the regenerant solution. The regenerant source vessel is in fluid communication with the resin vessel and operative to selectively provide the regenerant solution to the resin vessel. A rinse solution source in fluid communication with the resin vessel may selectively provide a rinse solution to the resin vessel. A regenerant waste outlet in fluid communication with the resin vessel may be adapted to receive therefrom a regenerant waste solution containing fluoride ions. A regenerant waste vessel may be further in fluid communication with said regenerant waste outlet to receive a selected quantity of the regenerant waste solution. A heat-exchange apparatus may be disposed proximate to the conduit and operative to transfer thermal energy away from the conduit. A reducing agent source in communication with the conduit may selectively introduce a reducing agent into the conduit, such as via a positive displacement metering pump.

The present invention also relates to an apparatus for use in removing fluorine from a selected environment that comprises first and second ion-exchange resins disposed in respective first and second resin vessels. A valve system includes a plurality of valves associated with a plurality of fluid pathways interconnecting selected ones of an inlet, a conduit, the first and second resin vessels, a regenerant source vessel, a rinse solution source and a regenerant waste outlet. The valve system includes various valve states permitting fluid flow. A controller may be operative to move the valve system into its respective states, and a pH monitor may generate a signal when the aqueous solution reaches a target pH value.

The present invention further relates to an apparatus for use in removing fluorine from a selected environment, comprising an inlet operative to provide fluorine gas from the environment to the resin vessel, in which is disposed an ion-exchange resin containing a selected volume percentage of water. The ion-exchange resin exchanges selected ions therein for fluoride

ions generated by contact of the fluorine gas with the ion-exchange resin having the volume percentage of water. A heat-exchange apparatus may be disposed proximate to the, resin vessel.

Finally, the present invention is directed to an apparatus for use in removing fluorine from a selected environment, comprising a scrubber in communication with the inlet and adapted to receive fluorine gas therefrom. The scrubber is operative to contact the fluorine gas with water thereby to form a solution of hydrofluoric acid. The resin vessel receives the solution from the scrubber, and the ion-exchange resin disposed in the resin vessel exchanges selected ions in the ion-exchange resin for fluoride ions in the solution when in contact therewith.

In accordance with a third aspect of the invention, there is provided an apparatus for use in removing fluorine from a selected environment, comprising: (a) an inlet in communication with the selected environment and operative to provide fluorine gas therefrom; (b) a conduit in communication with said inlet and adapted to receive fluorine gas therefrom, said conduit operative to transport an aqueous solution therethrough; (c) a first resin vessel in fluid communication with said conduit and selectively operative to receive the aqueous solution therefrom; (d) a first ion-exchange resin disposed in said first resin vessel and adapted to contact said aqueous solution, said first ion-exchange resin having an active state operative to exchange selected ions therein for fluoride ions in said aqueous solution when in contact therewith and an exhausted state operative to exchange the fluoride ions in said ion-exchange resin for the selected ions contained in a regenerant solution when in contact therewith. (e) a second resin vessel in fluid communication with said conduit and selectively operative to receive the aqueous solution therefrom; (f) a second ion-exchange resin disposed in said second resin vessel and adapted to contact said aqueous solution, said ion-exchange resin having an active state operative to exchange selected ions therein for fluoride ions in said aqueous solution when in contact therewith and an exhausted state operative to exchange the fluoride ions in said ion-exchange resin for the selected ions contained in the regenerant solution when in contact therewith; (g) a rinse solution source in fluid communication with said first resin vessel and said second resin vessel and operative to selectively provide a rinse solution respectively to said first resin vessel and said second resin vessel; (h) a regenerant source vessel adapted to receive the regenerant solution, said regenerant source vessel in fluid communication with said first resin vessel and said second resin vessel and operative to selectively provide the regenerant solution respectively to said

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first resin vessel and said second resin vessel; (i) a regenerant waste outlet in fluid communication with said first resin vessel and said second resin vessel and adapted to selectively receive from said respective first and second resin vessels a regenerant waste solution containing fluoride ions; 0) a valve system comprising a plurality of valves associated with a plurality of fluid pathways interconnecting selected ones of said inlet, said conduit, said first resin vessel, said second resin vessel, said regenerant source vessel, said rinse solution source and said regenerant waste outlet, whereby said valve system defines a first fluid pathway permitting fluid flow through said conduit and through said first resin vessel, a second fluid pathway permitting fluid flow from said regenerant source vessel through said second resin vessel and through said regenerant waste outlet, a third fluid pathway permitting fluid flow from said rinse solution source through said second ion-exchange resin and to said regenerant source vessel, a fourth fluid pathway permitting fluid flow through said conduit and through said second resin vessel, a fifth fluid pathway permitting fluid flow from said regenerant source vessel through said first resin vessel and through said regenerant waste outlet, a sixth fluid pathway permitting fluid flow from said rinse solution source through said first ion-exchange resin and to said regenerant source vessel, whereby in a first valve state fluid may flow along said first fluid pathway and said second fluid pathway, in a second valve state fluid may flow along said first fluid pathway and said third fluid pathway, in a third valve state fluid may flow along said fourth fluid pathway and said fifth fluid pathway, and in a fourth valve state fluid may flow along said fourth fluid pathway and said sixth fluid pathway.

In accordance with a fourth aspect of the invention, there is provided an apparatus for use in removing fluorine from a selected environment, comprising: (a) a resin vessel; (b) an inlet in communication with the selected environment and said resin vessel, said inlet operative to provide fluorine gas therefrom to said resin vessel; (c) an ion-exchange resin disposed in said resin vessel, said ionexchange resin containing a selected volume percentage of water and having an active state operative to exchange selected ions therein for fluoride ions generated by contact of said fluorine gas with said ion-exchange resin.

In accordance with a fifth aspect of the invention, there is provided an apparatus for use in removing fluorine from a selected environment, comprising: (a) an inlet in communication with the selected environment and operative to provide fluorine gas therefrom; (b) a scrubber in communication with said inlet and adapted to receive fluorine gas therefrom, said scrubber

operative to contact said fluorine gas with water thereby to form a solution of hydrofluoric acid; (c) a resin vessel in fluid communication with said scrubber and operative to receive said solution therefrom; and (d) an ion-exchange resin disposed in said resin vessel and adapted to contact said solution, said ion-exchange resin having an active state operative to exchange selected ions therein for fluoride ions in said solution when in contact therewith.

In accordance with a sixth aspect of the invention, there is provided a method for removing fluoride from an acidic solution containing fluoride ions and silica particles, comprising: filtering said acidic solution through a porous strong base anion resin thereby to remove silica particles disposed in said acidic solution; and contacting said acidic solution with a crosslinked poly-4- vinylpyridine resin or derivative thereof thereby to exchange selected ions therein for fluoride ions in said acidic solution.

In accordance with a seventh aspect of the invention, there is provided a method for removing fluoride from an acidic solution containing fluoride ions, comprising: doping an ion-exchange resin with an electron donor catalyst, wherein said ion-exchange resin is one having an active state operative to exchange selected ions therein for fluoride ions in said acidic solution when in contact therewith; and contacting said acidic solution with said ion-exchange resin.

In accordance with a eighth aspect of the invention, there is provided a method for removing fluoride from an acidic solution containing fluoride ions and an agent selected from an oxidizing agent and a reducing agent, comprising contacting said acidic solution with an ion-exchange resin that includes a functional group resistant to attack by oxidizing and reducing agents, said ion-exchange resin having an active state operative to exchange selected ions therein for fluoride ions in said acidic solution when in contact therewith.

In accordance with a ninth aspect of the invention, there is provided a method for removing fluorine from a selected environment, comprising contacting an ion-exchange resin with fluorine gas, wherein said ion-exchange resin contains a selected volume percentage of water and has an active state operative to exchange selected ions therein for fluoride ions generated by contact of said fluorine gas with said ion-exchange resin.

These and other objects of the present invention will become more readily appreciated and understood from a consideration of the following detailed description of the exemplary embodiment of the present invention when taken together with the accompanying drawings, in which.

BRIEF DESCRIPTION OF THE DRAWINGS

Figure 1a is a diagrammatic view of the method according to the present invention;

Figure 1b is a diagrammatic view of optional steps of the method of Figure 1a;

Figure 2a is a diagrammatic view of a first embodiment of an apparatus according to the present invention, showing the service cycle in operation;

Figure 2b is a diagrammatic view of the apparatus according to Figure 2a, showing a regeneration cycle in operation;

Figure 2c is a diagrammatic view of the apparatus of Figures 2a and 2b, showing a rinse/refill cycle in operation;

Figure 3a is a diagrammatic view of a second embodiment of an apparatus according to the present invention, showing a service cycle of a first resin and a regeneration cycle of a second resin;

Figure 3b is a diagrammatic view of the apparatus shown in Figure 3a, showing a service cycle of the first resin and a rinse/refill cycle of the second resin;

Figure 3c is a diagrammatic view of the apparatus of Figures 3a and 3b, showing a service cycle of the second resin and a regeneration cycle of the first resin;

Figure 3d is a diagrammatic view of the apparatus of Figures 3a through 3c, showing a service cycle of the second resin and a rinse/refill cycle of the first resin;

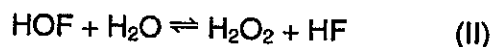
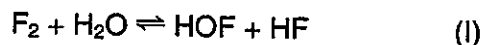
Figure 4 is a diagrammatic view of a third embodiment of an apparatus according to the present invention; and

Figure 5 is a diagrammatic view of a fourth embodiment of an apparatus according to the present invention.

DETAILED DESCRIPTION OF THE EXEMPLARY EMBODIMENTS

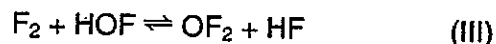
The present invention provides an efficient method, apparatus and system for removing fluorine gas from industrial manufacturing processes. It should be understood, however, that the present invention may be utilized in virtually any situation in which fluorine and/or fluoride collection and removal is desirable.

Generally, fluorine in use in semi-conductor manufacturing processes is mixed in a vacuum pump with a carrying gas, such as N₂ or other inert gases, preferably in a ratio of 40 liters of N₂ per 1.5 liters F₂. In the method of the present invention, this gas mixture is injected into an aqueous solution thereby to generate HF, which is believed to occur according to the following reactions I and II:



Further, HF is a weak acid, with a pK_a of 3.16. Accordingly, at low pH values, the transformation of F₂ to HF is discouraged. Adjustment of pH, such as by addition of alkali, poses the additional problem of generating

undesirable OF_2 which can be produced under alkaline conditions according to reaction III as follows:



Accordingly, in order to operate an optimum F_2 removal/abatement device it is desirable to reduce the HOF, such as by adding a reducing agent, and to keep a pH environment preferably of between 5 and 7. Further, because the reaction of F_2 with water may be exothermic, it is further desirable to dissipate heat generated thereby, such as through the use of a heat exchange device.

As shown in Figure 1a, then, the general method 10 of the present invention comprises service cycle 11, which includes injecting F_2 gas 12, preferably provided by an inlet 14, into a water stream 16, which is preferably a recirculating, or closed-loop, stream. A closed loop allows for higher flow rates and accordingly more efficient operation. HF 18 generated by the reaction of F_2 with water is passed through an ion-exchange resin 20, which is preferably disposed in a resin vessel 22. HF that contacts the ion-exchange resin 20 undergoes ion-exchange such that fluoride ions, F^- , are captured by ion-exchange resin 20. Alternatively, F_2 gas 12 may be injected directly into contact with ion-exchange resin 20 when the resin is of a type which has a high water volume percentage and is stable to oxidation by F_2 . In this case, F_2 gas 12 reacts with the moisture in the ion-exchange resin 20, thereby to generate HF 18 which undergoes ion-exchange with the functional groups of ion-exchange resin 20.

The preferred ion-exchange resin is a crosslinked poly-4-vinylpyridine resin and derivatives thereof, such as those manufactured by Reilly Industries, Inc., 1500 South Tibbs Avenue, Indianapolis, Indiana, under the tradenames ReillexTM 402 and 425. The pyridine functional groups of these resins are highly resistant to attack by oxidizing and reducing agents and have an unusually high capacity for HF. Further, these resins resist oxidation by hydrogen peroxide, H_2O_2 , postulated to be formed by the reaction of HOF and H_2O . It should be understood, however, that other ion-exchange resins may be utilized in accordance with the present invention. In particular, the

present invention contemplates resins with a weak base anion functionality, such as those having tertiary amines as main functional groups and either styrene or acrylic backbones. Additionally, the present invention contemplates resins having a strong base anion functionality, such as those having quaternary amines as main functional groups and either styrene or acrylic backbones. Exemplary weak base anion and strong base anion resins include those manufactured by Purolite®, located in Bala Cynwyd, PA, such as the A-860, A-845, A-100, A-870, A-600, A-510, A-500, A-500P, A-400, A-300, A-300E, A-200, and A-850 Purolite® ion-exchange resins.

Additionally, the present invention contemplates the use of resins which have been doped, or impregnated, with a catalyst to increase the rate of conversion of F_2 to F^- . The use of a catalyst may be desirable when the system conditions favor F_2 in the $F_2 \rightleftharpoons 2F^-$ equilibrium, such as under low pH, for example, or when a scrubber is not present in the system. The preferred catalyst is an electron donor, such as palladium or titanium metal, which accelerates the conversion of fluorine to fluoride. A resin may be doped with such a catalyst by, for example, contacting the resin with a palladium chloride salt solution and thereafter contacting the resin with an oxidizer thereby to precipitate the palladium metal in stoichiometric amounts. It should be appreciated that resins resistant to oxidation, such as the crosslinked poly-4-vinylpyridine resins and derivatives thereof discussed above, are particularly suitable for catalyst doping by this method.

It should be appreciated that other types of media may be substituted for the ion-exchange resin of the present invention. In particular, acid absorption or neutralizing media that sacrificially hydrates or neutralizes hydrofluoric acid, such as limestone or other calcium compounds, may be employed. However, such media are less preferred relative to media such as ion-exchange resins, which may be efficiently regenerated.

When an ion-exchange resin is utilized, the method of the present invention may additionally include a regeneration cycle 24 and a rinse/refill cycle 34, as shown in Figure 1b. The regeneration cycle 24 includes providing a regenerant solution 26, preferably from a regenerant source

vessel 28. Regenerant solution 26, which is preferably ammonium hydroxide, NH_4OH , is passed into resin vessel 22 and into contact with ion-exchange resin 20. Ion-exchange resin 20 undergoes ion-exchange with regenerant solution 26 thereby to form a regenerant waste 30 containing concentrated fluoride ion, F^- . When NH_4OH is used as the regenerant solution 26, regenerant waste 30 contains NH_4F salt. Regenerant waste 30 is then passed to waste outlet 32, whereby regenerant waste 30 may be either collected, such as in a dedicated container, or sent down a dedicated collection drain.

The rinse/refill cycle 34 includes providing a rinse solution 36, preferably de-ionized water, from a rinse source 38 such as a water inlet. Rinse solution 36 is passed through resin vessel 22 and in contact with ion-exchange resin 20, thereby to rinse any remaining regenerant solution 26 from resin vessel 22. Regenerant rinse solution 40 formed by rinsing resin vessel 22 may then be passed to regenerant source vessel 28, thereby to refill regenerant source vessel 28 with an aqueous solution whose concentration may thereafter be adjusted, such as by addition of concentrated NH_4OH to form the desired regenerant solution 26.

The method 10 of the present invention may additionally include one or more of the steps of cooling the water stream 16 to dissipate heat generated by the reaction of F_2 with water, monitoring the oxidation-reduction potential of water stream 16, adding a reducing agent to water stream 16 to assure decomposition of HOF formed during the reaction of F_2 with water, removing carrying gases provided along with F_2 gas 12 by inlet 14, monitoring pH for an indication that ion-exchange resin 22 is exhausted, signaling for the beginning of regeneration cycle 24, monitoring the concentration of regenerant solution 26 and adjusting the concentration of regenerant solution 26 to regeneration levels, such as by pumping concentrated solution into regenerant source vessel 28. In the case where F_2 gas 12 is pumped directly into resin vessel 22, the method may include a further step of hydrating ion-exchange resin 20 during service cycle 11, such as by providing de-ionized water to resin vessel 22 to replace water used in

reaction with F_2 , or by providing moisture, such as in vapor form, to resin vessel 22.

A general embodiment of the apparatus 100 according to the present invention is shown in Figures 2a – 2c. Here, apparatus 100 includes inlet 114, preferably a vacuum pump or eductor, resin vessel 122 having ion-exchange resin 120 disposed therein, regenerant source vessel 128 having regenerant solution 126 disposed therein, rinse source 138 operative to provide a rinse solution, and waste outlet 132, here shown as a container adapted to receive regenerant waste 130. Inlet 114, resin vessel 122, regenerant source vessel 128, rinse source 138, and waste outlet 132 are fluidly connected by conduit 142, which is adapted to receive a water stream. Pumps 146 and 148 are disposed in conduit 142, and each have an on state wherein they are operative to pump fluid through conduit 142 and an off state wherein they do not pump fluid. Valves 150, 152, 154, 156, 158, 160 and 162 are disposed in conduit 142 and are operative to move between a closed state preventing fluid flow therethrough and an open state allowing fluid flow therethrough.

Figure 2a shows the service cycle for apparatus 100. Here, F_2 gas 112 is injected from inlet 114 into water stream 116, which is a recirculating, or closed-loop, stream. Pump 146 is operative to pressurize and circulate water stream 116 in conduit 142. Valves 150 and 162 are open, while the remaining valves are closed. HF laden water in water stream 116 flows through resin vessel 122 where it undergoes ion-exchange with ion exchange resin 120. Preferably, water stream 116 flows through resin vessel 122 in an up-flow direction, creating an expanded, or fluidized, resin bed. Carrying gas 164, such as N_2 , is removed at top of resin vessel 122 which has a free volume 165 capable of allowing carrying gas 164 to separate from the water stream 116, where it can then be directed to a location for further processing, such as by a scrubber.

When ion-exchange resin 120 is at full capacity of F^- , a regeneration cycle begins as shown in Figure 2b. Here, valves 150 and 162 are closed and pump 146 is turned off. Preferably, inlet 114 is also closed or turned off

as appropriate. Valves 160, 152 and 154 are opened and pump 148 is turned on. Regenerant solution 126, preferably ammonium hydroxide, is pumped from regenerant source vessel 128 and through resin vessel 122 which undergoes ion-exchange with ion-exchange resin 120, thereby to produce regenerant waste 130. When ammonium hydroxide solution is used as the regenerant solution 126, ammonium fluoride solution is formed as the regenerant waste 130 resulting from regeneration of ion-exchange resin 120. The concentration, as well as rate of flow through resin vessel 122, of regenerant solution 126 is preferably adjusted according to the concentration of regenerant waste 130 that is desired. Preferably, regenerant waste 130 is a concentrated stream of ammonium fluoride that is easily disposed of without requiring excessive sludge hauling.

Once ion-exchange resin 122 has been regenerated, a rinse cycle begins, as shown in Figure 2c. Here, valves 160 and 154 are closed and valves 156 and 158 are opened, while pump 148 is turned off. Rinse solution 136, provided by rinse source 138, passes through resin vessel 122 to rinse any remaining regenerant solution 126 therefrom. Regenerant rinse solution 140 then flows to regenerant source vessel 128, where regenerant rinse solution 140 may be recycled to form a new regenerant solution 126, such as by adding concentrated regenerant 167, preferably ammonium hydroxide, to regenerant source vessel 128 until a desired regeneration concentration of regenerant solution 126 is achieved. To the extent understood by the ordinarily skilled artisan, a concentration monitor/control may be used to automatically adjust the concentration of NH_4OH to regeneration levels by pumping concentrated solution to regenerant source vessel 128 as desired.

Once the rinse/refill cycle has completed, valves 152, 156 and 158 are closed and valves 150 and 162 are opened, pump 146 is turned on, and if necessary inlet 114 is turned on or opened as appropriate, thereby to begin the service cycle again.

The various on/off and open/closed states of valves and pumps during the operation cycles for apparatus 100 is summarized in Table 1 below:

Table 1

	Service Cycle	Regeneration Cycle	Rinse/Refill Cycle
Pump 146	ON	OFF	OFF
Pump 148	OFF	ON	OFF
Valve 150	OPEN	CLOSED	CLOSED
Valve 152	CLOSED	OPEN	OPEN
Valve 154	CLOSED	OPEN	CLOSED
Valve 156	CLOSED	CLOSED	OPEN
Valve 158	CLOSED	CLOSED	OPEN
Valve 160	CLOSED	OPEN	CLOSED
Valve 162	OPEN	CLOSED	CLOSED

A more preferred embodiment of the present invention is shown in Figures 3a – 3d. Here, apparatus 200 includes a dual resin setup, wherein two ion-exchange resins are utilized such that one of the ion-exchange resins can be in the service cycle while the other of the ion-exchange resins undergoes the regeneration and rinse/refill cycles. Thus, it becomes unnecessary to interrupt the fluorine removal/abatement process, because a service cycle can be continuously performed by the apparatus.

Apparatus 200 includes a vacuum pump 214, which is operative to supply F_2 gas 212 to a conduit 242 which interconnects various components of the apparatus 200. Preferably, a heat exchanger 268 is disposed in thermal communication with conduit 242 immediately downstream of juncture 270 where F_2 gas 212 is injected into a water stream 216 circulating through conduit 242. Additionally, apparatus 200 preferably includes a reducing agent source 272 in fluid communication with conduit 242 and operative to provide a reducing agent 274 which is capable of reducing HOF which may be formed by the reaction of F_2 and water. To the extent understood by the ordinarily skilled artisan, the addition of reducing agent 274 from reducing agent source 272 into water stream 216 is preferably controlled by an oxidation-reduction potential (ORP) monitor, which signals for reducing agent 274 to be pumped from reducing agent source 272 when an oxidation-

reduction potential is detected. A mixer 276 is also preferably provided to optimally mix reducing agent 274 into water stream 216. It should be understood that the present invention contemplates the use of integrated heat-exchangers and mixers that may be available in the art, such that heat exchanger 268 and mixer 276 may be disposed in one apparatus. Additionally, a pH monitor 278 is preferably provided, whereby the pH monitor is capable of monitoring the pH of the water stream 216 and operative to provide a signal when the pH decreases below a selected threshold.

First resin vessel 222 and second resin vessel 223 are provided in fluid communication with conduit 242, and each resin vessel contains ion-exchange resin 220 and 221, respectively. Rinse source 238 is further in fluid communication with conduit 242, and is operative to provide de-ionized water 236. Regenerant source vessel 228 is operative to provide dilute ammonium hydroxide 226. Waste outlet 232 is operative to receive ammonium fluoride regenerant waste 230 resulting from regeneration of either of ion-exchange resins 220 or 221.

Pumps 244, 246 and 248 are disposed in conduit 242 and are operative in an on state to pump fluid through conduit 242. It should be understood that pump 244 may be unnecessary if pump 246 provides sufficient circulation through conduit 242. Valves 250 through 263 are disposed in conduit 242 and are operative to move between a closed state preventing fluid flow therethrough and an open state allowing fluid flow therethrough.

As shown in Figures 3a and 3b, first resin vessel 222 can undergo a service cycle while second resin vessel 223 undergoes both a regeneration cycle and a rinse/refill cycle. In particular, as shown in Figure 3a, pumps 244, 246 and 248 are turned on, valves 250, 253, 255, 261 and 262 are opened and valves 251, 252, 254, 256, 257, 258, 259, 260 and 263 are closed thereby to work a service cycle in first resin vessel 222 and a regeneration cycle in second resin vessel 223. With respect to the service cycle of first resin vessel 222, F₂ gas 212 from vacuum pump 214 is injected

into water stream 216 which circulates through first resin vessel 222 and undergoes ion-exchange with ion-exchange resin 220. Carrying gas, such as N_2 may be removed at free volume 265. Concurrently, dilute NH_4OH 226 from regenerant source vessel 228 is pumped by pump 248 through resin vessel 223 thereby to regenerate ion-exchange resin 221 to form NH_4F regenerant waste 230 which is sent to waste outlet 232.

As shown in Figure 3b, once ion-exchange resin 221 is regenerated, a rinse/refill cycle begins on second resin vessel 223, while the service cycle continues on first resin vessel 222. Here, pump 248 is turned off, valves 257 and 259 open and valves 255 and 261 close. De-ionized water 236 from rinse source 238 is passed through second resin vessel 223 thereby to rinse away any excess NH_4OH and to form regenerant rinse solution 240 which is passed to regenerant source vessel 228 for reuse in forming the NH_4OH regenerant solution 226. Concentrated NH_4OH 267 may be added to regenerant source vessel 228 to adjust the concentration of NH_4OH regenerant solution 226 as desired.

Once the rinse/refill cycle has completed, valves 259, 253 and 257 are closed and the service cycle continues on first resin vessel 222 until ion-exchange resin 220 is exhausted, as indicated by a signal from pH monitor 278 when the pH of water stream 216 declines below a selected threshold thereby indicating that HF is no longer undergoing ion-exchange with ion-exchange resin 220.

At this time, as shown in Figures 3c and 3d, second resin vessel 223 undergoes a service cycle while first resin vessel 222 undergoes regeneration and rinse/refill cycles. In particular, as shown in Figure 3c, pumps 244, 246 and 248 are turned on, valves 251, 252, 254, 260 and 263 are opened and valves 250, 253, 255, 256, 257, 258, 259, 261, and 262 are closed. With respect to the service cycle through second resin vessel 223, F_2 gas from vacuum pump 214 is injected into water stream 216 which circulates through second resin vessel 223 thereby undergoing ion-exchange with ion-exchange resin 221. Carrying gas such as N_2 can be removed at free volume 266. First resin vessel 222 undergoes regeneration as dilute

NH_4OH is pumped by pump 248 from regenerant source vessel 228 through first resin vessel 222 thereby undergoing ion-exchange with ion-exchange resin 220 to form NH_4F regenerant waste 230 which is sent to waste outlet 232.

As shown in Figure 3d, once ion-exchange resin 220 is regenerated, pump 248 is turned off, valves 254 and 260 are closed and valves 256 and 258 are opened. Second resin vessel 223 continues undergoing a service cycle. De-ionized water 236 from rinse source 238 passes through first resin vessel 222 thereby to rinse any excess NH_4OH therefrom. The regenerant rinse solution 240 is then passed to regenerant source vessel 228 where it is recycled for use in NH_4OH regenerant solution 226, the concentration of which may be adjusted by addition of concentrated ammonium hydroxide 267.

Once rinse/refill cycle has completed, valves 258, 252 and 256 are closed and the service cycle continues on second resin vessel 223 until ion-exchange resin 221 is exhausted, as indicated by a signal from pH monitor 278 when the pH of water stream 216 declines below a selected threshold thereby indicating that HF is no longer undergoing ion-exchange with ion-exchange resin 220. At this point, a service cycle on first resin vessel 222 and a regeneration cycle on second resin vessel 223 begins again as shown in Figure 3a.

The various on/off and open/closed states of valves and pumps during the operation cycles for apparatus 200 is summarized in Table 2 below:

Table 2

	First resin service cycle / second resin regen. cycle	First resin service cycle / second resin rinse cycle	Second resin service cycle / first resin regen. cycle	Second resin service cycle / first resin rinse cycle
Pump 244	ON	ON	ON	ON
Pump 246	ON	ON	ON	ON
Pump 248	ON	OFF	ON	OFF
Valve 250	OPEN	OPEN	CLOSED	CLOSED
Valve 251	CLOSED	CLOSED	OPEN	OPEN
Valve 252	CLOSED	CLOSED	OPEN	OPEN
Valve 253	OPEN	OPEN	CLOSED	CLOSED
Valve 254	CLOSED	CLOSED	OPEN	CLOSED
Valve 255	OPEN	CLOSED	CLOSED	CLOSED
Valve 256	CLOSED	CLOSED	CLOSED	OPEN
Valve 257	CLOSED	OPEN	CLOSED	CLOSED
Valve 258	CLOSED	CLOSED	CLOSED	OPEN
Valve 259	CLOSED	OPEN	CLOSED	CLOSED
Valve 260	CLOSED	CLOSED	OPEN	CLOSED
Valve 261	OPEN	CLOSED	CLOSED	CLOSED
Valve 262	OPEN	OPEN	CLOSED	CLOSED
Valve 263	CLOSED	CLOSED	OPEN	OPEN

A third embodiment of apparatus 300 is shown in Figure 4. Here, service, regeneration and rinse/refill cycles operate similarly to the dual resin embodiment of Figures 3a – 3d. Figure 4 shows operation that corresponds to Figure 3a for the second embodiment of the apparatus, showing a service cycle of first resin vessel 322 having ion-exchange resin 320 disposed therein, and a regeneration cycle of second resin vessel 323 having ion-exchange resin 321 disposed therein. However, in this embodiment, during a service cycle of one of resin vessels 322 or 323, F₂ gas 312 is injected from vacuum pump 314 directly into the resin bed of one or the other of ion-

exchange resins 320 and 321, which each contain a volume percentage of water of preferably approximately 42%. Again, the preferred resin is a resin containing pyridine functional groups, such as the crosslinked poly-4-vinylpyridine resins manufactured by Reilly. The pyridine resins are very stable such that F_2 generally will not hurt their structure by oxidation.

As shown in Figure 4, outlets 315 and 317 of vacuum pump 314 are attached to the bottom of each of resin vessels 322 and 323, respectively, and valves 350 and 351 direct F_2 gas 312 to either resin vessel. In this embodiment, there is sufficient water in the ion-exchange resins 320 and 321, respectively, for the reaction of F_2 and water that forms HF to take place. Preferably, cooling jackets 380 and 381 are respectively disposed proximate to resin vessels 322 and 323, thereby to dissipate any heat generated by the reaction of F_2 and water. Again, excess carrying gas, such as N_2 , may be removed at the free volumes 365 and 366 disposed in resin vessels 322 and 323 respectively.

The ion-exchange resins 320 and 321 will become rehydrated during their respective regeneration cycles, given that the regeneration cycle is an aqueous cycle. However, if a selected type of resin contains insufficient water for the HF reaction to take place until the resin is exhausted with F^- , it may be necessary to provide a separate rehydration cycle to either of ion-exchange resins 320 and 321 during their respective service cycles by providing de-ionized water 336 from rinse source 338 through valves 358 or 359. Alternatively, moisture may be injected in vapor form from an external source into resin vessels 322 and 323 during their respective service cycles, thereby to provide sufficient water for the reaction.

The various on/off and open/closed states of valves and pumps during the operation cycles for apparatus 300 is summarized in Table 3 below:

Table 3

	First resin service cycle / second resin regen. cycle	First resin service cycle / second resin rinse cycle	Second resin service cycle / first resin regen. cycle	Second resin service cycle / first resin rinse cycle
Pump 348	ON	OFF	ON	OFF
Valve 350	OPEN	OPEN	CLOSED	CLOSED
Valve 351	CLOSED	CLOSED	OPEN	OPEN
Valve 352	CLOSED	CLOSED	OPEN	OPEN
Valve 353	OPEN	OPEN	CLOSED	CLOSED
Valve 354	CLOSED	CLOSED	OPEN	CLOSED
Valve 355	OPEN	CLOSED	CLOSED	CLOSED
Valve 356	CLOSED	CLOSED	CLOSED	OPEN
Valve 357	CLOSED	OPEN	CLOSED	CLOSED
Valve 358	CLOSED	CLOSED	CLOSED	OPEN
Valve 359	CLOSED	OPEN	CLOSED	CLOSED
Valve 360	CLOSED	CLOSED	OPEN	CLOSED
Valve 361	OPEN	CLOSED	CLOSED	CLOSED

It should be appreciated that in this embodiment, it is possible to remove the T-shaped portion of conduit 342 shown in Figure 4 that includes valves 353, 355 and 357, such that the apparatus only utilizes—for the regeneration and rinse/refill cycles of both resin vessels—the T-shaped portion of conduit 342 that includes valves 352, 354 and 356.

As shown in Figure 5, a fourth embodiment of the apparatus 400 according to the present invention may be seen as an attachment to existing conventional scrubbers, such as are currently used by the semi-conductor manufacturing industry. Here, the F₂ gas 412, again typically mixed with a 40:1 ration of N₂, would be brought into a scrubber 482, thereby to generate HF by reaction with water. The water stream 416 from the scrubber is then cooled with heat exchanger 468, and a reducing agent 474 from reducing agent source 472 is injected into water stream 416 to assure decomposition

of HOF, and further mixing may be provided by mixer 476. Operation of the service, regeneration and rinse/refill cycles of the apparatus 400 are similar to that discussed with respect to the apparatus 200 of Figures 3a – 3d. Here, it should be noted that resin vessels 422 and 423 need not include any free volume for removing carrying gases such as N_2 , given that such gases 464 are removed by scrubber 482 and can be transported for further processing. A closed loop operation of water stream 416 is preferred, which allows for higher flow rates through the scrubber 482 and accordingly more efficient scrubbing.

In all embodiments of the present invention, it may be desirable to remove any SiO_2 or other compounds of silica in the waste stream. That is, since HF in the semiconductor industry is used extensively for silicon wafer etching, and is also a product of the scrubbing of excess F_2 gas in the chamber clean process, there is generally SiO_2 and other silica compounds in the waste stream. Due to the low pH, these compounds form gelatinous solids, or colloidal silica, generally in concentrations of 300 – 400 ppm. Such particles are generally difficult to remove using conventional filtration methods. Accordingly, to remove such silica particles in the waste stream, the present invention contemplates the use of a strong base anion resin of high porosity, such as the Purolite 501-P and equivalent resins, to filter silica particles from the solution. These resins have a “filtration” functionality in view of their porosity, but also have the advantage of capturing silica particles on account of the anion-resin charge. Such resins can be used as a first step in the treatment process, prior to removing the fluoride ion in the solution by ion-exchange. It should be understood that the high porosity resins can be incorporated in disposable cartridges that can be replaced as necessary with fresh cartridges containing the resin. Alternatively, the high porosity resins can be disposed in resin vessels through which the silica containing solution is passed; in such case, the resins can be regenerated with the same regenerant solution used to regenerate the HF removal resin.

Accordingly, the present invention has been described with some degree of particularity directed to the exemplary embodiment of the present

invention. It should be appreciated, though, that the present invention is defined by the following claims construed in light of the prior art so that modifications or changes may be made to the exemplary embodiment of the present invention without departing from the inventive concepts contained herein.

I claim:

1. A method for removing fluorine gas from a selected environment, comprising the steps of:

(a) contacting the fluorine gas from the environment with a selected quantity of water, thereby to generate an acidic solution of hydrofluoric acid; and

(b) contacting said acidic solution of hydrofluoric acid with an ion-exchange resin having an active state operative to exchange selected ions therein for fluoride ions in said acidic solution when in contact therewith.

2. A method according to claim 1 wherein the step of contacting the fluorine gas with said selected quantity of water includes contacting a continuous stream of water with a continuous stream of fluorine gas.

3. A method according to claim 1 wherein the step of contacting the fluorine gas with said selected quantity of water is accomplished by injecting said fluorine gas into said water.

4. A method according to claim 1 wherein the selected environment includes silica particles, and including the step of filtering said solution of hydrofluoric acid through a porous strong base anion resin thereby to remove silica particles disposed in said solution.

5. A method according to claim 1 wherein the step of contacting said solution with said ion-exchange resin is accomplished by passing said solution of hydrofluoric acid through a resin vessel in which said ion-exchange resin is disposed.

6. A method according to claim 1 wherein said ion-exchange resin is selected from the group consisting of weak-base anion exchange resins and strong base anion exchange resins.

7. A method according to claim 6 wherein said ion-exchange resin is selected from the group consisting of crosslinked poly-4-vinylpyridine resins and derivatives of crosslinked poly-4-vinylpyridine resins.

8. A method according to claim 7 wherein said ion-exchange resin is selected from the group consisting of Reillex™ 402 and Reillex™ 425.

9. A method according to claim 1 including the step of doping said ion-exchange resin with an electron donor catalyst.
10. A method according to claim 9 wherein said catalyst is selected from the group consisting of palladium or titanium.
11. A method according to claim 9 wherein the step of doping is accomplished by contacting said ion-exchange resin with a salt of said catalyst and thereafter contacting said ion-exchange resin with an oxidizing agent.
12. A method according to claim 1 wherein said ion-exchange resin is capable of chemically shifting between said active state and an exhausted state operative to exchange the fluoride ions in said ion-exchange resin for the selected ions contained in a regenerant solution when in contact therewith, and including the step of regenerating said ion-exchange resin by contacting said ion-exchange resin with the regenerant solution thereby to form a selected regenerant waste product containing the fluoride ions.
13. A method according to claim 12 wherein said regenerant solution is an ammonium hydroxide solution.
14. A method according to claim 12 including the step of rinsing said ion-exchange resin with a rinse solution after the step of regenerating said ion-exchange resin.
15. A method according to claim 14 wherein said rinse solution is de-ionized water.
16. A method according to claim 14 including the step of replenishing said regenerant solution with said rinse solution after the step of rinsing said ion-exchange resin.
17. A method according to claim 12 including the step of collecting said regenerant waste product in a storage vessel.
18. A method according to claim 1 including the step of cooling said solution of hydrofluoric acid prior to the step of contacting said solution of hydrofluoric acid with said ion-exchange resin.

19. A method according to claim 18 wherein the step of cooling is accomplished by contacting said solution of hydrofluoric acid with a heat-exchange apparatus.

20. A method according to claim 1 including the step of adding a reducing agent to said solution of hydrofluoric acid prior to the step of contacting said solution of hydrofluoric acid with said ion-exchange resin.

21. An apparatus for use in removing fluorine from a selected environment, comprising:

(a) an inlet in communication with the selected environment and operative to provide fluorine gas therefrom;

(b) a conduit in communication with said inlet and adapted to receive fluorine gas therefrom, said conduit operative to transport an aqueous solution therethrough;

(c) a resin vessel in fluid communication with said conduit and operative to receive the aqueous solution therefrom; and

(d) an ion-exchange resin disposed in said resin vessel and adapted to contact said aqueous solution, said ion-exchange resin having an active state operative to exchange selected ions therein for fluoride ions in said aqueous solution at an acidic pH when in contact therewith.

22. An apparatus according to claim 21 wherein said inlet includes an injector operative to inject the fluorine gas into said conduit.

23. An apparatus according to claim 22 wherein said injector is selected from the group consisting of a vacuum pump and an eductor.

24. An apparatus according to claim 21 wherein said resin vessel receives said aqueous solution in a fluid compartment thereof, said resin vessel further including a chamber proximate to said fluid compartment and sized and adapted to permit a gas disposed in said aqueous solution to separate therefrom and enter said chamber.

25. An apparatus according to claim 24 wherein said chamber is in communication with a scrubber operative to receive the gas from said chamber.

26. An apparatus according to claim 21 wherein said ion-exchange resin is selected from the group consisting of weak-base anion exchange resins and strong base anion exchange resins.
27. An apparatus according to claim 26 wherein said ion-exchange resin is selected from the group consisting of crosslinked poly-4-vinylpyridine resins and derivatives of crosslinked poly-4-vinylpyridine resins.
28. An apparatus according to claim 27 wherein said ion-exchange resin is selected from the group consisting of ReillexTM 402 and ReillexTM 425.
29. An apparatus according to claim 28 wherein said ion-exchange resin is doped with an electron donor catalyst.
30. An apparatus according to claim 29 wherein said catalyst is selected from the group consisting of palladium or titanium.
31. An apparatus according to claim 21, wherein said ion-exchange resin is capable of chemically shifting between said active state and an exhausted state operative to exchange the fluoride ions in said ion-exchange resin for the selected ions contained in a regenerant solution when in contact therewith, said apparatus including a regenerant source vessel adapted to receive the regenerant solution, said regenerant source vessel in fluid communication with said resin vessel and operative to selectively provide the regenerant solution to said resin vessel.
32. An apparatus according to claim 31 wherein said regenerant source vessel is operative to selectively provide an ammonium hydroxide solution to said resin vessel.
33. An apparatus according to claim 31 including a rinse solution source in fluid communication with said resin vessel and operative to selectively provide a rinse solution to said resin vessel.
34. An apparatus according to claim 33 wherein said rinse solution source is operative to provide de-ionized water to said resin vessel.
35. An apparatus according to claim 31 including a regenerant waste outlet in fluid communication with said resin vessel and adapted to receive therefrom a regenerant waste solution containing fluoride ions.

36. An apparatus according to claim 35 including a regenerant waste vessel in fluid communication with said regenerant waste outlet and sized and adapted to receive a selected quantity of the regenerant waste solution.

37. An apparatus according to claim 21 including a heat-exchange apparatus proximate to said conduit and operative to transfer thermal energy away from said conduit.

38. An apparatus according to claim 21 including a reducing agent source in communication with said conduit and operative to selectively introduce a reducing agent into said conduit.

39. An apparatus according to claim 38 wherein said reducing agent source is operative to inject said reducing agent into said conduit via a positive displacement metering pump.

40. An apparatus for use in removing fluorine from a selected environment, comprising:

(a) an inlet in communication with the selected environment and operative to provide fluorine gas therefrom;

(b) a conduit in communication with said inlet and adapted to receive fluorine gas therefrom, said conduit operative to transport an aqueous solution therethrough;

(c) a first resin vessel in fluid communication with said conduit and selectively operative to receive the aqueous solution therefrom;

(d) a first ion-exchange resin disposed in said first resin vessel and adapted to contact said aqueous solution, said first ion-exchange resin having an active state operative to exchange selected ions therein for fluoride ions in said aqueous solution when in contact therewith and an exhausted state operative to exchange the fluoride ions in said ion-exchange resin for the selected ions contained in a regenerant solution when in contact therewith.

(e) a second resin vessel in fluid communication with said conduit and selectively operative to receive the aqueous solution therefrom;

(f) a second ion-exchange resin disposed in said second resin vessel and adapted to contact said aqueous solution, said ion-exchange resin having an active state operative to exchange selected ions therein for fluoride ions in said aqueous solution when in contact therewith and an exhausted state operative to exchange the fluoride ions in said ion-exchange resin for the selected ions contained in the regenerant solution when in contact therewith;

(g) a rinse solution source in fluid communication with said first resin vessel and said second resin vessel and operative to selectively provide a rinse solution respectively to said first resin vessel and said second resin vessel;

(h) a regenerant source vessel adapted to receive the regenerant solution, said regenerant source vessel in fluid communication with said first resin vessel and said second resin vessel and operative to selectively provide the regenerant solution respectively to said first resin vessel and said second resin vessel;

(i) a regenerant waste outlet in fluid communication with said first resin vessel and said second resin vessel and adapted to selectively receive from said respective first and second resin vessels a regenerant waste solution containing fluoride ions;

(j) a valve system comprising a plurality of valves associated with a plurality of fluid pathways interconnecting selected ones of said inlet, said conduit, said first resin vessel, said second resin vessel, said regenerant source vessel, said rinse solution source and said regenerant waste outlet, whereby said valve system defines a first fluid pathway permitting fluid flow through said conduit and through said first resin vessel, a second fluid pathway permitting fluid flow from said regenerant source vessel through said second resin vessel and through said regenerant waste outlet, a third fluid pathway permitting fluid flow from said rinse solution source through said second ion-exchange resin and to said regenerant source vessel, a fourth fluid pathway permitting fluid flow through said conduit and through said second resin vessel, a fifth fluid pathway permitting fluid flow from said

regenerant source vessel through said first resin vessel and through said regenerant waste outlet, a sixth fluid pathway permitting fluid flow from said rinse solution source through said first ion-exchange resin and to said regenerant source vessel, whereby in a first valve state fluid may flow along said first fluid pathway and said second fluid pathway, in a second valve state fluid may flow along said first fluid pathway and said third fluid pathway, in a third valve state fluid may flow along said fourth fluid pathway and said fifth fluid pathway, and in a fourth valve state fluid may flow along said fourth fluid pathway and said sixth fluid pathway.

41. An apparatus according to claim 40 wherein said valve system includes a fifth valve state whereby fluid may flow only along said first fluid pathway, and a sixth valve state whereby fluid may flow only along said fourth fluid pathway.

42. An apparatus according to claim 40 including a controller operative to move said valve system into its respective states.

43. An apparatus according to claim 42 including a pH monitor operative to generate a signal when said pH monitor measures a target pH value of the aqueous solution, said controller being operative to move said valve system into its respective states in response to said signal.

44. An apparatus for use in removing fluorine from a selected environment, comprising:

- (a) a resin vessel;
- (b) an inlet in communication with the selected environment and said resin vessel, said inlet operative to provide fluorine gas therefrom to said resin vessel;
- (c) an ion-exchange resin disposed in said resin vessel, said ion-exchange resin containing a selected volume percentage of water and having an active state operative to exchange selected ions therein for fluoride ions generated by contact of said fluorine gas with said ion-exchange resin.

45. An apparatus according to claim 44 including a heat-exchange apparatus proximate to said resin vessel and operative to transfer thermal energy away from said conduit.

46. An apparatus according to claim 45 wherein said heat-exchange apparatus includes a cooling jacket sized and adapted to contact a major portion of an outer surface of said resin vessel.

47. An apparatus according to claim 44 wherein said ion-exchange resin is resistant to oxidation by fluorine gas.

48. An apparatus for use in removing fluorine from a selected environment, comprising:

(a) an inlet in communication with the selected environment and operative to provide fluorine gas therefrom;

(b) a scrubber in communication with said inlet and adapted to receive fluorine gas therefrom, said scrubber operative to contact said fluorine gas with water thereby to form an acidic solution of hydrofluoric acid;

(c) a resin vessel in fluid communication with said scrubber and operative to receive said acidic solution therefrom; and

(d) an ion-exchange resin disposed in said resin vessel and adapted to contact said acidic solution, said ion-exchange resin having an active state operative to exchange selected ions therein for fluoride ions in said acidic solution when in contact therewith.

49. A method according to claim 1 wherein said acidic solution of hydrofluoric acid is at a pH of between 5 and 7.

50. A method for removing fluoride from an acidic solution containing fluoride ions and silica particles, comprising:

(a) filtering said acidic solution through a porous strong base anion resin thereby to remove silica particles disposed in said acidic solution; and

(b) contacting said acidic solution with a crosslinked poly-4-vinylpyridine resin or derivative thereof thereby to exchange selected ions therein for fluoride ions in said acidic solution.

51. A method according to claim 50 wherein said silica particles exist in said acidic solution as fluorosilicates, and wherein said porous strong base anion resin preferentially absorbs fluorosilicates over fluoride ions.

52. A method according to claim 50 wherein said porous strong base anion resin is in the chloride form prior to the step of filtering.

53. A method according to claim 50 wherein said crosslinked poly-4-vinylpyridine resin or derivative thereof is in the OH form prior to the step of contacting said acidic solution therewith.

54. A method for removing fluoride from an acidic solution containing fluoride ions, comprising:

(a) doping an ion-exchange resin with an electron donor catalyst, wherein said ion-exchange resin is one having an active state operative to exchange selected ions therein for fluoride ions in said acidic solution when in contact therewith; and

(b) contacting said acidic solution with said ion-exchange resin.

55. A method according to claim 54 wherein said ion-exchange resin is a crosslinked poly-4-vinylpyridine resin or derivative thereof.

56. A method according to claim 54 wherein said catalyst is selected from palladium or titanium.

57. A method according to claim 54 wherein the step of doping is accomplished by contacting said ion-exchange resin with a salt of said catalyst and thereafter contacting said ion-exchange resin with an oxidizing agent.

58. A method for removing fluoride from an acidic solution containing fluoride ions and an agent selected from an oxidizing agent and a reducing agent, comprising contacting said acidic solution with an ion-exchange resin that includes a functional group resistant to attack by oxidizing and reducing agents, said ion-exchange resin having an active state operative to exchange selected ions therein for fluoride ions in said acidic solution when in contact therewith.

59. A method according to claim 58 wherein said ion-exchange resin includes pyridine functional groups.

60. A method according to claim 59 wherein said ion-exchange resin is selected from crosslinked poly-4-vinylpyridine resins and derivatives thereof.

61. A method according to claim 58 wherein said acidic solution contains an agent selected from OF_2 and H_2O_2 .

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62. An apparatus according to claim 47 wherein said ion-exchange resin includes pyridine functional groups.

63. An apparatus according to claim 62 wherein said ion-exchange resin is selected from crosslinked poly-4-vinylpyridine resins and derivatives thereof.

64. A method for removing fluorine from a selected environment, comprising contacting an ion-exchange resin with fluorine gas, wherein said ion-exchange resin contains a selected volume percentage of water and has an active state operative to exchange selected ions therein for fluoride ions generated by contact of said fluorine gas with said ion-exchange resin.

65. A method according to claim 64 wherein said ion-exchange resin is resistant to oxidation by fluorine gas.

66. A method according to claim 65 wherein said ion-exchange resin includes pyridine functional groups.

67. A method according to claim 66 wherein said ion-exchange resin is selected from crosslinked poly-4-vinylpyridine resins and derivatives thereof.